THE 1904 M_S6.8 M_W7.0-7.2 CAPE TURNAGAIN, NEW ZEALAND, EARTHQUAKE

G. L. Downes[1]

SUMMARY

The 1904 August 09 NZT (August 08 UT) M_S6.8 earthquake caused widespread structural and chimney damage from Napier to Wellington and was felt over a large part of New Zealand. Other than a brief paper in 1905, and determinations of its surface wave magnitude in the last 20 years, little has been done to better locate the earthquake or detail its effects.

Comprehensive data have now been obtained from searches of historical documents, including newspapers, private and government papers, as well as instrumental records. Interpretation of the intensity data shows that the earthquake was probably centred near Cape Turnagain at relatively shallow depth. The paucity of aftershocks suggests that the earthquake occurred either on the subduction interface, or in the lower seismicity band or upper mantle of the subducting Pacific Plate. The area encompassed by the higher intensity isoseismals suggests the earthquake had a magnitude greater than the calculated surface wave magnitude $M_S6.75 \pm 0.14$ — possibly as high as M_W7.2. At this magnitude, the earthquake becomes a more significant event in New Zealand's historical record, and certainly the largest earthquake suspected of rupturing the plate interface along the Hikurangi Margin.

A notable feature of the earthquake is the chimney and parapet damage caused in parts of Wellington Central Business District, approximately 170 km from the epicentre. Much of the city and inner suburbs experienced MM5-6, while MM6-7 occurred in several areas, mostly in those areas that are recognised as possibly susceptible to shaking enhancement, but also in several locations outside these areas.

The 1904 Cape Turnagain earthquake has several implications for seismic hazard dependent on whether it was intra-slab or on the plate interface. Of particular importance, are the questions whether the damage in Wellington is exceptional and could represent microzone, focussing or directivity effects; the goodness of fit of the intensity distribution to modelled isoseismals using published attenuation relations; the compatibility of the magnitude with the maximum magnitude/magnitude cut-offs used in this area in the New Zealand Probabilistic Seismic Hazard model; and finally, the possibility that the 1904 earthquake might characterise plate interface earthquakes in southern Hawke's Bay

INTRODUCTION

The earthquake at about 10.20 am Tuesday August 9 1904 (NZT) (August 08 22.50 UT) was felt over most of the North Island, and a large part of the South Island, of New Zealand. It was most strongly felt, causing widespread chimney and structural damage, between Napier and Wellington on the east, and south coast of the North Island respectively (Figure 1). This part of New Zealand is characterised by high seismicity as the result of oblique subduction of the Pacific Plate beneath the Australian Plate along the Hikurangi Trough (Figure 1). In the last 160 years (the period of organised European settlement in New Zealand), the area is known to have experienced at least nine large magnitude ($M \geq 6.5$) shallow earthquakes (depth $\leq$ 30 km) (Figure 1), including two of the three largest historical events known, the M_W8.1-8.2 1855 Wairarapa and the M_S7.8 1931 Hawke's Bay earthquakes.

Prior to the preliminary investigations of Downes (1992, 1995), the 1904 earthquake had been little discussed in the scientific literature, and little investigated since 1905. Hogben's (1905) epicentre for the earthquake, at 42.39ºS 178.97ºE, ~300 km southeast of Cape Turnagain (see Figures 1 & 2 for place names mentioned in the text), is clearly too far offshore for the known damage. His epicentre was based on inadequate arrival times recorded by a network of telegraph operators who had been organised to act as "felt reporters". Despite the reporters being instructed to check the correct time with Wellington daily, their reports were probably accurate to the nearest half-minute at best.

The only instruments in New Zealand at the time — Milne seismographs at Wellington and Christchurch — were of little use, as they had poor timing and were not designed for recording local shocks. Further, the Christchurch instrument was out of action at the beginning of the earthquake.

Based on Hogben's (1905) brief description of the earthquake's effects and on other sparse historical data within the NZ Seismological Observatory's files, an epicentre at 41.0ºS 176.5ºE was tentatively adopted for seismic hazard studies (Smith & Berryman, 1986), and subsequently used for surface wave magnitude determination studies (Dowrick & Smith, 1990). A preliminary investigation based on more extensive information by Downes (1992) gave a location at 40.6ºS 176.8ºE at lower crustal depth.

The most recent calculation of surface wave magnitude $M_S6.75 \pm 0.14$ (Dowrick & Rhoades, 1998) is considerably lower than the earlier non-instrumental estimates of M7.5 (for example: Smith & Berryman, 1986; Grant-Taylor *et al*., 1974), but compatible with Dowrick & Smith's (1990)

[1] *GNS Science, Lower Hutt New Zealand, (Member)*

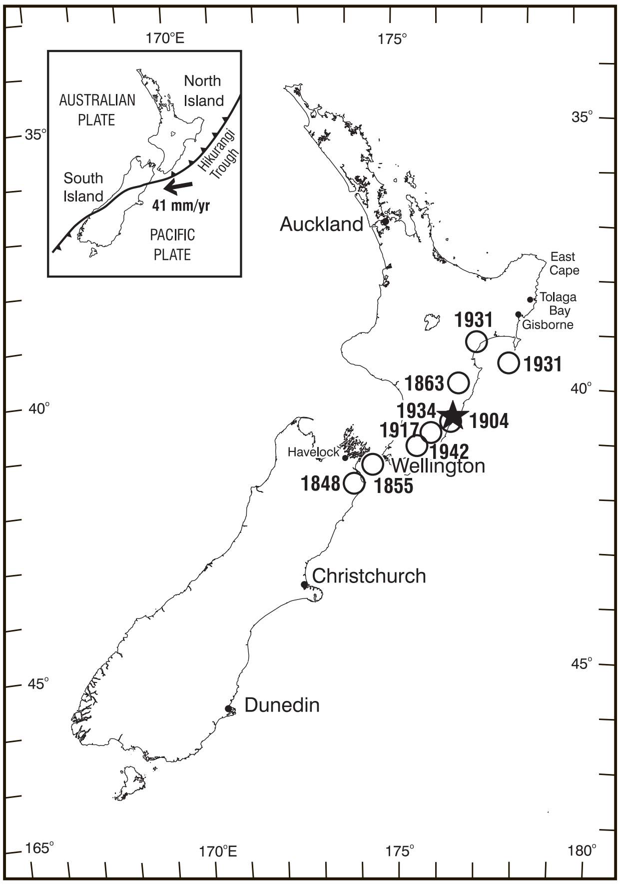

Figure 1: Map of the North Island of New Zealand showing the main features of the plate boundary and the location of the large magnitude earthquakes (M ≥ 7.0, depth ≤ 30 km) known to have occurred since 1840, including the new location (starred) of the 1904 Cape Turnagain earthquake.

M_S6.73, and Abe & Noguchi's (1983) M_S6.9. At this magnitude, the 1904 earthquake ranks as one of the larger historical earthquakes in one of New Zealand's most active seismic zones and as such, needed to be better located and its effects better documented. In particular, it was important to determine whether the damaged parapets and fallen chimneys reported to have occurred in Wellington were caused by the mainshock, and were within the bounds of expected damage some 170 km from the most damaged area and presumed epicentre.

In this study, we analyse data from a comprehensive collection of historical descriptive accounts and instrumental data, providing felt and ground damage data and a new isoseismal map, as well as data on seiching and a possible tsunami. Evidence for aftershocks is presented as well as the inferences that can be made from the small number recorded. The likely epicentre, depth and magnitude of the earthquake and their uncertainties are discussed.

It will be shown that the 1904 earthquake has some characteristics that make it important in the historical earthquake record and that have significant implications for seismic hazard assessment of this part of the east coast dependent on whether it was intra-slab or on the plate interface. Of particular importance is the possibility that the 1904 earthquake might characterise plate interface earthquakes in southern Hawke's Bay, and hence, possibly impact on the potential for this part of the plate boundary to produce very large interface earthquakes. Other features that are discussed are the possible occurrence of microzone, focussing or directivity effects; the goodness of fit of the intensity distribution to modelled isoseismals using existing attenuation relations; the compatibility of the magnitude with the maximum magnitude/magnitude cut-offs used in this area in the New Zealand Probabilistic Seismic Hazard model.

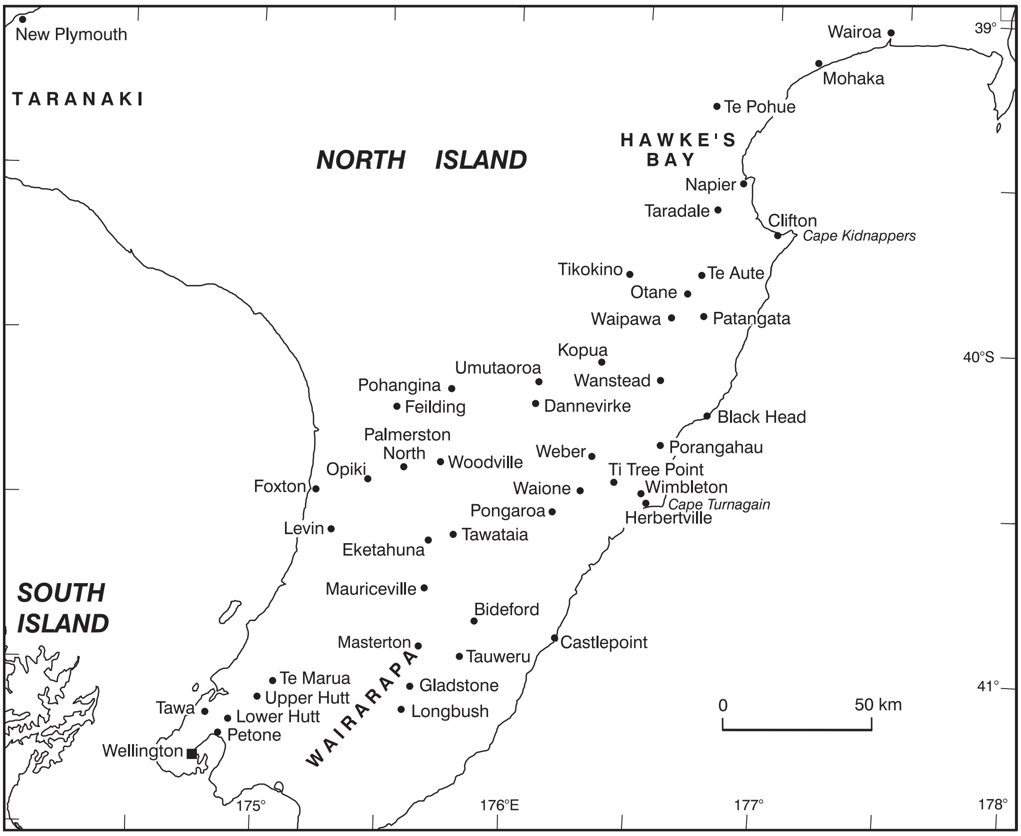

Figure 2: Map showing the location of places referred to in the main body of the text that are not indicated on Figure 1.

MACROSEISMIC DATA

Newspaper reporting of the 1904 August 9 (NZT) earthquake was particularly extensive and detailed. To supplement newspaper accounts, many other sources of information were sought. In particular, diary and other personal accounts were sought at the Alexander Turnbull Library (ATL), the National Library of New Zealand, and Hawke’s Bay Art Gallery and Museum. A 1904 correspondence file of Henry Hill at ATL deserves special mention.

Hill, Inspector of Schools for Hawke's Bay 1878-1915, and apparently a friend of the previously mentioned George Hogben, had an avid interest in all the sciences, including geology. He wrote a number of papers in the *Transactions and Proceedings of the Philosophical Society* and was president of the Hawke's Bay Branch in 1903. Hill experienced the 1904 August 9 earthquake on a school inspection at Otane, and on his way to Patangata the next day he observed, and his companion sketched, the effects of sand fountains in the Waipawa River bed (shown in Figure 3). A few days later he took photographs of similar effects in the Tutaekuri River in Napier. The photographs have not been located. Early in September, Hill requested all schoolmasters in his district, from East Cape to Woodville, to answer a questionnaire about the effects of the earthquake. Eighteen of these letters (Hill 1904a) as well as Hill's observations (Hill 1904b) provide invaluable first-hand evidence.

Using the Dowrick (1996) version of the MM intensity scale Modified Mercalli intensities are assigned at locations where sufficient information is available. These are listed in Table 1, summarised in the Appendix 1, and plotted in Figure 4. As is the usual practice, intensities are preferably assigned on the basis of building and contents damage rather than on ground damage or environmental effects, such as sand fountaining, landslide or ground fissuring, as these effects can occur over a range of intensities dependent on ground conditions.

The sparse rural population within the highest intensity area means that the building stock was primarily domestic wooden dwellings with mostly un-reinforced brick chimneys. There were few masonry or brick buildings. By necessity, the assignment of intensities above MM6 has been based primarily on the extent of chimney damage. However, where masonry structures have been present, the assigning of intensities MM7 and MM8 on the basis of chimney damage alone has proved reasonably reliable.

Isoseismal map

The isoseismal map is shown in Figure 4. While there is a reasonable number of intensities, large gaps occur in critical areas, viz. between Waione and Bideford and along the coast between Porangahau and Napier. The highest intensity, MM8 (MM8-9 at Herbertville) was experienced from north of Porangahau to near Castlepoint,. Clear delineation of the MM8 isoseismal is difficult. An intensity of MM8 has been assigned also to Mauriceville and Gladstone. Possibly these areas were susceptible to some shaking enhancement due to the soil structure or the topography, as within short distances effects tended to be markedly less. The MM7 isoseismal extends from Napier to south of Castlepoint and includes Dannevirke and Masterton. The MM6 isoseismal extends from Mohaka in the north to Wellington in the south and Feilding and Palmerston North to the west. Information on effects south of Foxton is poor and it is possible that this area should not be included in the MM6 isoseismal. The MM5 isoseismal extends into the southern Taranaki region. There appears to be little expression of it south of Cook Strait, with only Havelock reaching MM5. However, as few household objects are broken at this intensity and the damage might have been considered too trivial to report compared to other areas, MM5 may not be recognisable. Also, as the earthquake occurred during daylight hours, the criterion “most sleepers awakened” cannot be used.

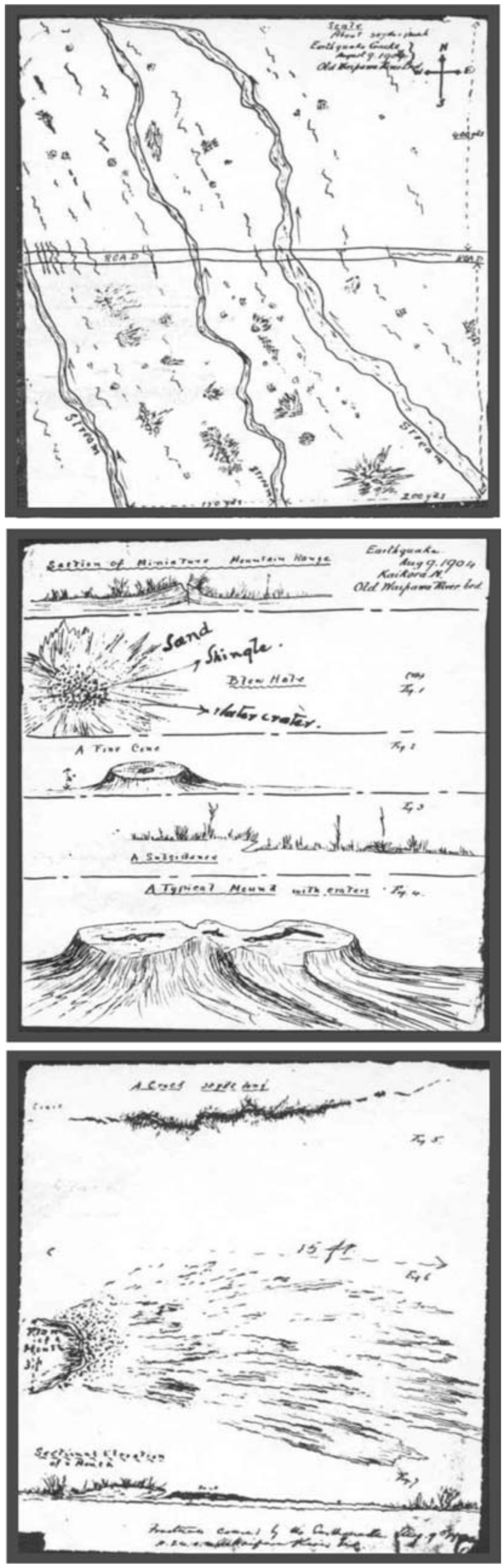

Figure 3: Sketches of sand fountaining features in the old Waipawa River bed between Waipawa and Patangata described by Hill and sketched by J. McCaughley (MS-Papers-6005, Alexander Turnbull Library, National Library of New Zealand).

Comparison of the isoseismal map with model maps developed from the attenuation models of Dowrick & Rhoades (1999) suggests that the M_S magnitude of the earthquake may be too low. The magnitude and depth of the earthquake are discussed further in the *Magnitude* section of this paper.

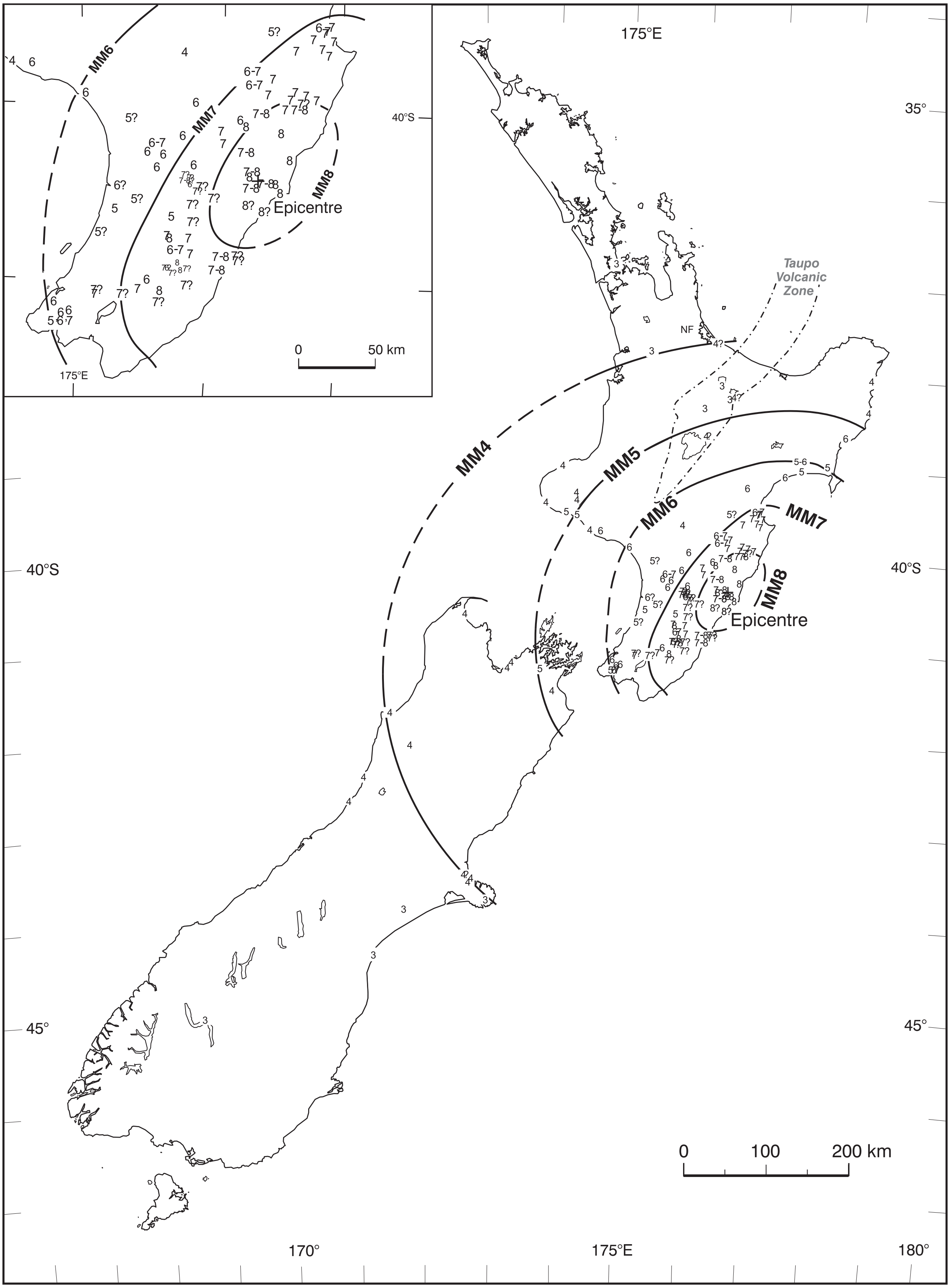

Figure 4: ***Isoseismal map of the 1904 Cape Turnagain earthquake. Inset: Detail of inner isoseismals.***

Table 1. Intensities caused by the 1904 Cape Turnagain earthquake.

NORTH ISLAND	Kaitawa MM7?	Petone MM6	Wairere MM7
Akitio MM8?	Kuripuni MM6?	Pohangina MM6	Wairoa MM5
Alfredton MM7?	Lake Rotomahana MM4?	Pongaroa MM8?	Wakarara MM6-7
Apiti MM6	Levin MM5	Porangahau MM8	Wanganui MM6
Atiamuri MM3	Longbush MM7?	Puketapu MM6	Wanstead MM8
Auckland MM3	Lower Hutt MM6	Rangitumau MM6-7	Waverley MM6
Awahuri MM6	Makuri MM7?	Rotorua MM3	Weber MM8
Ballance MM7?	Manaia MM5	Shannon MM5?	Wellington MM5-MM7
Bideford MM7	Mangahao MM7-8?	Stratford MM4	Weraiti MM7?
Blackburn MM6-7	Mangatainoka MM7?	Taihape MM4	Whakataki MM7?
Bramerton MM7?	Mangatarata MM7-8	Takapau MM7-8	Whanawhana MM5?
Brancepeth MM7?	Maraekakaho MM7	Tamumu MM7?	Whangaehu Station MM8
Bunnythorpe MM6	Marton MM5?	Tane MM7?	Whareama MM7-8
Carterton MM6	Masterton MM7	Taradale MM7	Wimbledon MM8
Castlepoint MM7?	Mauriceville MM8	Taupo MM4?	Woodville MM6
Clive MM7	Mauriceville West MM7	Tauranga MM4?	
Dannevirke MM7	Mohaka MM6	Tauweru MM8	SOUTH ISLAND
Edenham MM7	Morere MM5	Tawa MM6	Akaroa MM3
Eketahuna MM5	Napier MM7	Te Aroha NF	Ashburton MM3
Eltham MM4	New Plymouth MM4	Te Marua MM7?	Blenheim MM4
Featherston MM7?	Ngapaeruru MM7-8	Te Pohue MM6	Christchurch MM4?
Feilding MM6-7	Ngaturi MM7?	Tikokino MM7	Collingwood MM4
Foxton MM6?	Norsewood MM6	Tinui MM7-8	Greymouth MM4
Frasertown MM5-6	Omahu MM7	Titree Point MM7-8	Havelock MM5
Gisborne MM6	Onga Onga MM7	Tolaga Bay MM4	Hokitika MM4
Gladstone MM8	Opunake MM4	Umutaoroa MM7	Lyttelton MM4
Greenmeadows MM7	Ormondville MM8	Upper Hutt MM7	Nelson MM4
Greytown MM7	Otaki MM5?	Waimangu MM3	Queenstown MM3
Hamilton MM3	Otane MM7	Waione MM7-8	Reefton MM4
Hastings MM7	Pahiatua MM6	Waipatiki MM7-8	Sumner MM4
Havelock North MM7	Palmerston North MM6	Waipawa MM7	Timaru MM3
Hawera MM5	Patangata MM7	Waipiro Bay MM4	Wakapuaka MM4
Herbertville MM8-9	Patea MM4	Waipukurau MM7	Westport MM4

Distribution of damage within Wellington City

The Cape Turnagain earthquake was felt in Wellington as approximately 15-20 seconds of mild tremors followed by stronger vibrations, some observers saying that the final "kick" was the most vigorous part of the shaking. The earthquake was also noted as prolonged and severe, and the worst since 1855. It was felt generally throughout the city, although it was not noticed by some on bicycles, or otherwise taking part in vigorous activity. Damage was quite variable, from MM6 and MM7 in parts the Central Business District (CBD), Newtown, and Tinakori Road (Figure 5) to strongly felt with no damage (MM5). Brooklyn, a new hill suburb at the time, is specifically identified as having no damage.

Given the high level of newspaper coverage of the earthquake's effects, the lack of specific damage reports for inner and more distant parts of Wellington, such as Thorndon, Karori or Miramar, is interpreted as indicating little or no significant damage. Hence other than in areas specified in newspapers, MM5 seems to have been experienced generally. This is consistent with the earthquake being strongly felt at Tawa with "no serious damage" (MM5?), and in the lower Hutt Valley, goods were upset in some shops, several chimneys only were damaged, a few plate glass windows were broken, and one or two very old and flimsy wooden buildings at Petone were said to be "strained" (MM6 at most).

In contrast, in parts of the CBD, there was considerable stock damage, some chimneys fell, some parapets and gables were damaged or fell, brick walls were cracked, and windows were broken. In a few locations, many chimneys fell. Appendix 2 details known building damage in Wellington City from newspaper accounts. Building locations are derived from newspaper accounts, Wise's Street directories of the time and the Cyclopedia of New Zealand (1905). While some buildings and locations are specifically named, other areas are only defined by such terms as *Upper Willis Street or Newtown*.

Figure 5 shows the distribution of the more extensively damaged buildings, corresponding to MM7, in relation to the published Ground Shaking Hazard Maps for Wellington (Kingsbury & Hastie, 1992). The more seriously damaged buildings coincide fairly well with mapped Zone 5 and Zone

3-4 areas, noting that only a small part of the area marked Zone 5 had been reclaimed by 1904 (shown on Figure 5). The most seriously damaged districts, Newtown Upper Willis Street, and Cambridge/Kent Terrace, also lie within areas that contain significant areas of Zones 5 and 3-4. The most notable mismatch is the high chimney damage in Zone 1-2 in Brougham Street, and along Ellice Street, which spans several zones, including Zone 3-4 and 5. Also, the Zone 5 area delineating the old Te Aro swamp is remarkable for the lack of damage, except at its southern extremity, where College Street experienced damage to many household chimneys, some damaging roofs and interiors.

Damage corresponding to MM6 and MM6-7 is also predominantly in the 3-4 Zone, with some in Zone 5 and very little in Zones 1 and 2.

Figure 5 also shows the relationship of the damaged areas to the shoreline prior to the 1855 M_W8.1-8.2 Wairarapa earthquake, which raised the Lambton Harbour area about 1.2 m (Grapes & Downes, 1997). In the Lambton Quay/ Lower Willis Street area, very little damage occurred on the landward side of pre-1855 earthquake shoreline. In the Courtenay Place area, sparse damage extended inland of the 1855 beach.

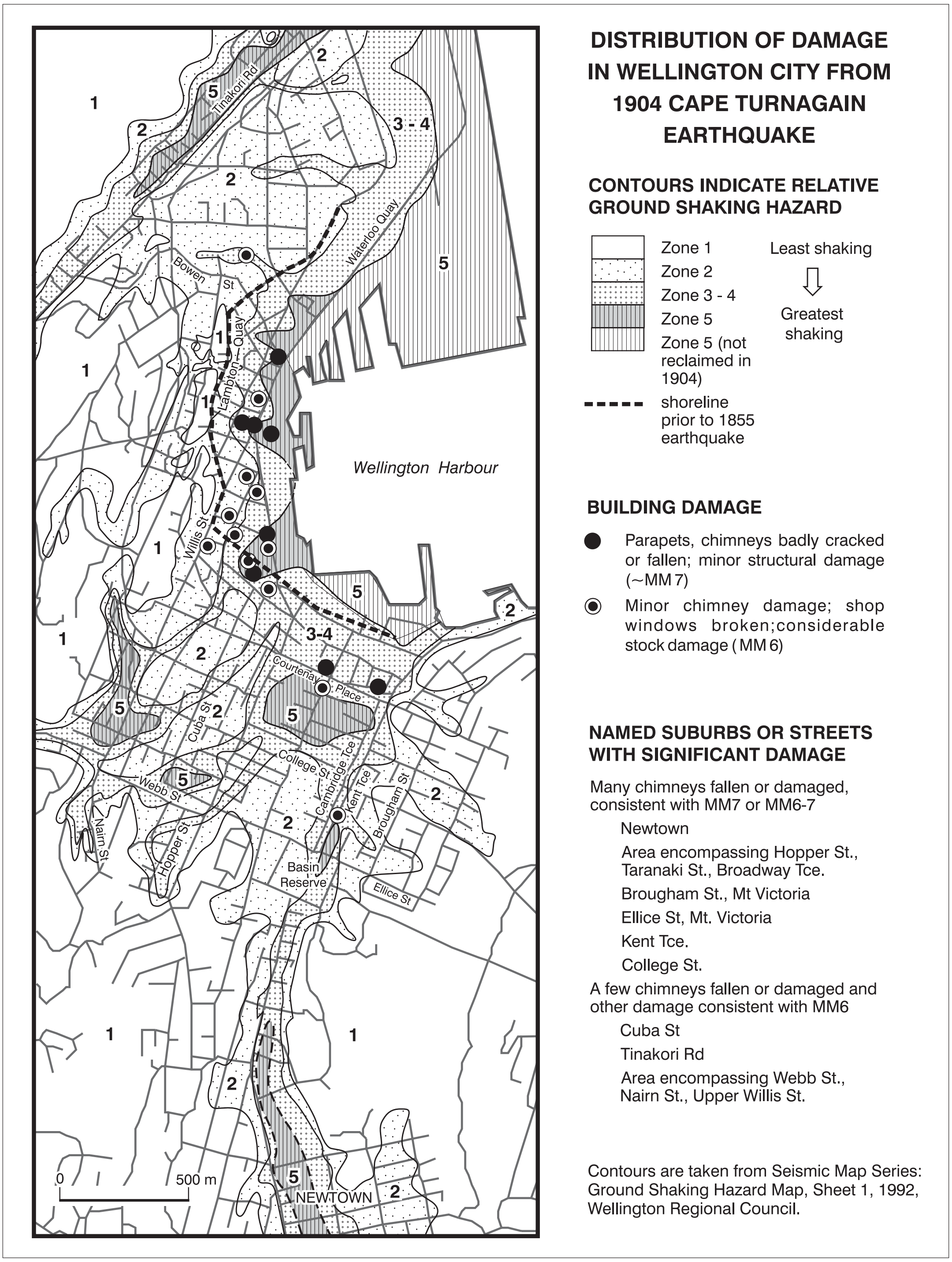

Figure 5: ***The distribution of more seriously damaged buildings in the Wellington City area in relation to the Ground Shaking Hazard Maps for Wellington (Kingsbury & Hastie, 1992). Note that some parts of Zone 5 had not been reclaimed by 1904. These are shown by different shading. The shoreline prior to the 1855 M_W8.1-8.2 Wairarapa earthquake, which raised the Wellington Central Business District by about 1.2 m, is shown as a heavy line.***

As will be shown in the section on *Aftershocks*, there is no evidence of a second earthquake nearer to Wellington at the same time as the Cape Turnagain earthquake. Hence, the damage in Wellington was caused by the 1904 Cape Turnagain earthquake, the epicentre of which will be shown in the next section to be approximately 170 km from Wellington, and its distribution calls into question whether shaking enhancement over a small area of Wellington City occurred.

The evidence for shaking enhancement is not unequivocal for several reasons. Firstly, the occurrence of isolated MM7 intensities within MM6 or even MM5 isoseismals is not unusual (Dowrick & Rhoades, 1999). Further, there were many buildings in the areas potentially subject to enhancement that were not damaged to MM7 level. On the other hand, few buildings and chimneys outside these areas seem to have been damaged, consistent with a microzone effect occurring.

Landslides and liquefaction

The 1904 earthquake caused ground damage in the form of landslides, subsidence of bridge approaches, slumping and cracking of roads and river banks, and sand ejections at many locations throughout an area of about 6,000 km^2 east of a line between Gladstone, Waipawa and Napier. As the earthquake occurred shortly after a heavy snowstorm in the Wairarapa and Hawke's Bay areas at the end of winter, soils were probably saturated, and conditions ideal for ground damage to occur.

Most ground damage occurred within the MM7 and MM8 isoseismal areas. The most extensive landslide damage occurred within the MM8 area. However, most landslides seem to have been small, except those from the coastal cliffs from Clifton to Cape Kidnappers, at Black Head and about Cape Turnagain, and from a high steep river-cut terrace near Gladstone. A few tonnes of rock fell from the cliffs at the Bluff in Napier. This took several days to clear. Outside the MM7 and MM8 areas, there were only isolated instances of ground damage attributed at the time to the earthquake, including one or two "slips from a ridge" in Tolaga Bay (MM5), minor road edge cracking at Mohaka (MM6), minor earth cracks near Te Pohue (MM6), "one or two heavy slips" from river terraces at Pohangina (MM6), and ground cracks near Levin (MM6).

Settlement and cracks in roads and riverbanks, while extensive in the MM8 zone, were mostly of modest nuisance value only and do not seem to have caused extensive delays, disruption or damage, possibly because they occurred in sparsely populated farming areas. Road bridge approaches subsided near Te Aute, on the Akitio Road near Ti Tree Point and at Tauweru, while settlement affected railway lines near Mauriceville and delayed trains for 24 hours at the Kopua viaduct. Cracks on top of a ridge at a location near Ti Tree Point are interpreted as probable ridge renting.

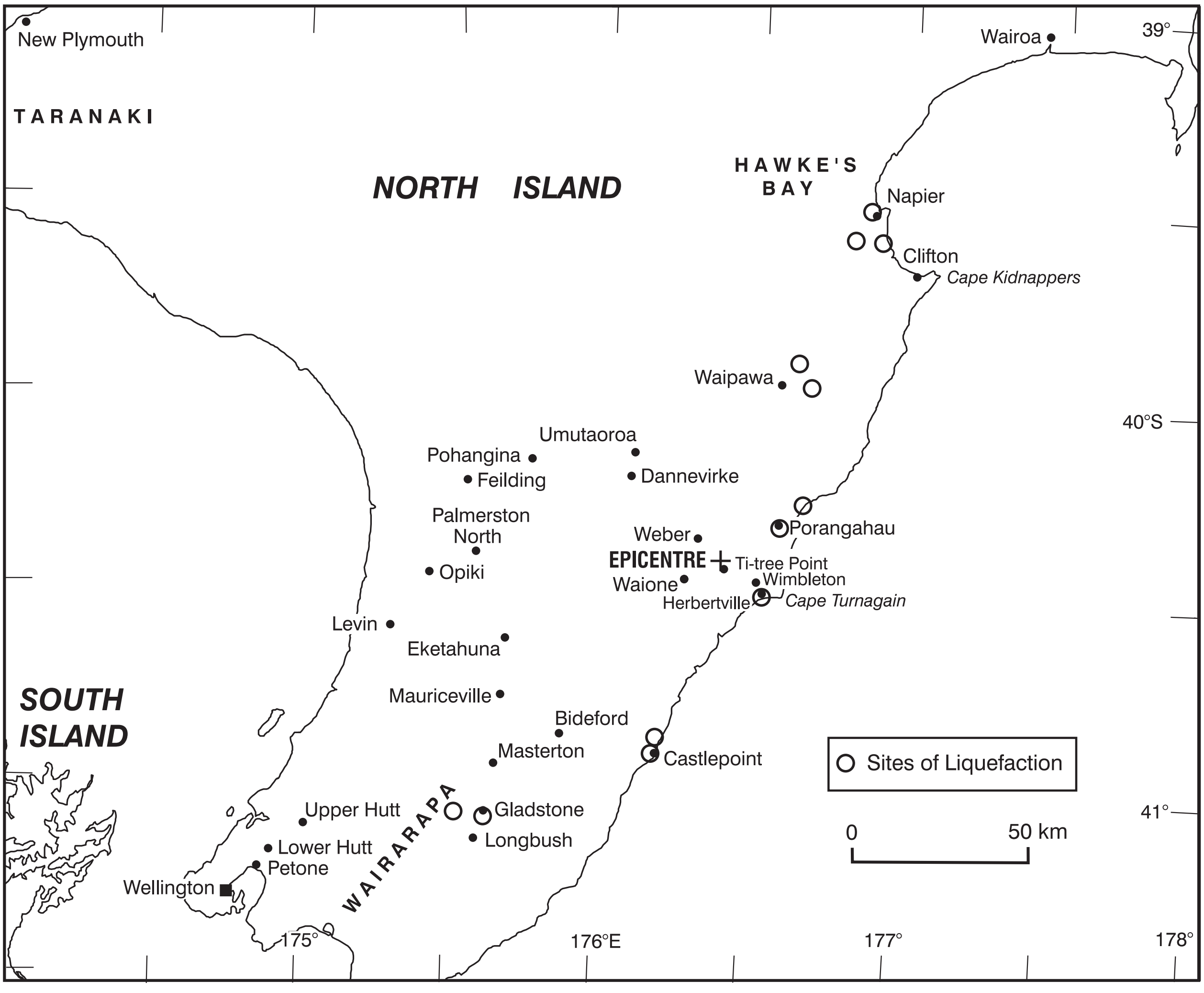

Figure 6: ***Map showing the locations of liquefaction (circles) in the form of sand fountains and lateral spreading caused by the 1904 Cape Turnagain earthquake.***

The earthquake also caused sand ejections and/or lateral spreading, some of which were quite extensive, at up to thirteen sites at twelve locations (Appendix 3; Figure 6). All well identified occurrences lie within the MM7 and MM8 isoseismals, consistent with the criteria of the MM intensity scale. Some occurred in areas known to have sand fountaining in more recent earthquakes, notably in 1931 (Hancox *et al.* 1997), 1934 (Downes *et al.* 1999), and in June and August 1942 (Downes *et al.* 2001). Changes in water run-off in drainage ditches at Makerua Swamp, near Opiki, in the MM6 zone can probably be attributed to liquefaction also. This area had extensive sand fountains in the June and August 1942 earthquakes (Downes *et al.*, 2001). Prior to Downes (1992), and Hancox *et al.* (1997) (the data for which was mainly based on the study reported here), no sand-fountaining or liquefaction-induced ground damage had been associated with the 1904 earthquake (Fairless & Berrill, 1984). As has been found in recent studies of the 1934 Pahiatua (Downes, *et al*., 1999) and 1942 Wairarapa earthquakes (Downes *et al.*, 2001), the occurrence of liquefaction is far more common and widespread than previously recognised.

Casualties

The earthquake caused a few minor injuries, and collapse and death of an elderly man at Nireaha, west of Eketahuna, presumably from stroke or heart attack.

Lifelines

Electricity supplies seem to have been little interrupted by the earthquake, possibly because their distribution was limited. Although accounts frequently describe the swaying of telegraph poles, and the rattling and intertwining of wires, the telegraph service was interrupted between Napier and Wellington for no more than a few hours. Domestic water supplies were mostly interrupted by the leaking or breaking of joints of internal water pipes, or damage to external tanks.

Fires

The school at Tamumu, near Waipawa, and two houses, at Wanstead and Tawataia, were burnt down reportedly as the result of earthquake damage to chimneys. Several other fires were extinguished before extensive damage was done.

Tsunami?

One of Hill's correspondents, at Mohaka, reported a large wave that he associated with the earthquake. No time was given. A tsunami could have been generated if the earthquake had been shallow enough to cause significant vertical seafloor deformation, or by a submarine landslide triggered by strong shaking. A tsunami from sources near Cape Turnagain would arrive at Mohaka about an hour after the earthquake. However, it is unlikely a landslide source near Cape Turnagain would cause a significant wave at Mohaka without causing a large tsunami locally, which was not reported. A more probable source of a tsunami at Mohaka, would be the large earthquake-induced coastal landslides from the cliffs at Cape Kidnappers.

A report of a second possible tsunami appeared in the *Wairoa Guardian* two weeks after the mainshock. A heavy shock was reportedly felt at Mohaka on August 25 at 10.30 UT (2200 NZT) was "followed immediately by the uprising of the sea". This earthquake was not felt a short distance away in Wairoa nor reported elsewhere and hence its occurrence and that of an associated tsunami is doubtful. Some confusion with the August 8 shock, which occurred at almost the same time of day, cannot be discounted.

A search for tidal records from Napier and Gisborne, which might confirm either tsunami, was not successful and the validity of the tsunamis remains in doubt.

Seismic seiche

Seiches seem to have been generated by the earthquake in the Waipawa, Porangahau, Manawatu and Wanganui rivers, and in Lake Rotomahana. At the latter place, "the guide in charge of the boats had his hand badly injured endeavouring to hold the boat against the jetty" (Poverty Bay Herald August 17 1904), when water in the lake became agitated and rose 600 mm.

EPICENTRE OF THE 1904 AUGUST 9 (AUGUST 8 UT) CAPE TURNAGAIN EARTHQUAKE

The Cape Turnagain earthquake was recorded on the worldwide Milne seismograph network (see BAAS, 1905) and on other seismographs of various types in Europe. Very few seismograms are extant. Seismograms from Wellington, Christchurch, Honolulu, and Melbourne only have been found. However, arrival times of various phases and maximum amplitudes of seismograms from the Milne network are recorded in British Association for the Advancement of Science (BAAS, 1905), while published and unpublished station bulletins for several other European stations (Potsdam, Göttingen, Strasbourg, and De Bilt) as well as Melbourne, Australia, are available.

The quality of the records, the accuracy of recorded arrival times (to the nearest 0.1 minute at best, most often to the nearest 0.5-1.0 minute or more), the lack of consistently reliable absolute time, as well as poor and sparse station distribution, mean that these records cannot be used to calculate an instrumental epicentre. Nevertheless, recorded arrival times at Wellington (P wave), at Melbourne and Perth (P and S waves), and an S wave arrival at Honolulu, are within a minute of the expected time of arrival for a shallow earthquake originating in New Zealand on August 8 at about 2250.5 UT, the origin time that best fits the New Zealand and Australian seismogram data as well as descriptive accounts. Relative to this origin time, PKP arrivals are within 1-6 minutes of the expected arrival time, but few other listed arrivals can be reliably identified as specific body wave, or surface wave arrivals, and the times of the maximum surface wave amplitudes are very scattered (Figure 7).

Assuming the origin time given above, a best fit line through the assumed surface wave arrivals corresponds to a velocity of 3.8 km/s, while the best fit line through the maximum amplitude times corresponds to a group velocity of 3.0 km/s. Allowing the origin time to vary does not markedly improve the fit. Both velocities are credible and consistent with a surface wave group velocity of 3.09 km/sec found for the 1914 October 6 East Cape earthquake by Reyners (pers. comm.), for which the data were considerably less scattered.

Without instrumental records, the maximum intensity, the isoseismal map, aftershock distribution, or descriptive accounts must be used to determine an epicentre. Descriptive accounts are usually considered highly unreliable. However, observations of the 1904 earthquake's sequential effects on trees in the distant landscape at Umutaoroa and near Mauriceville are credible. They help to constrain the epicentre, and to some extent, the depth of the earthquake.

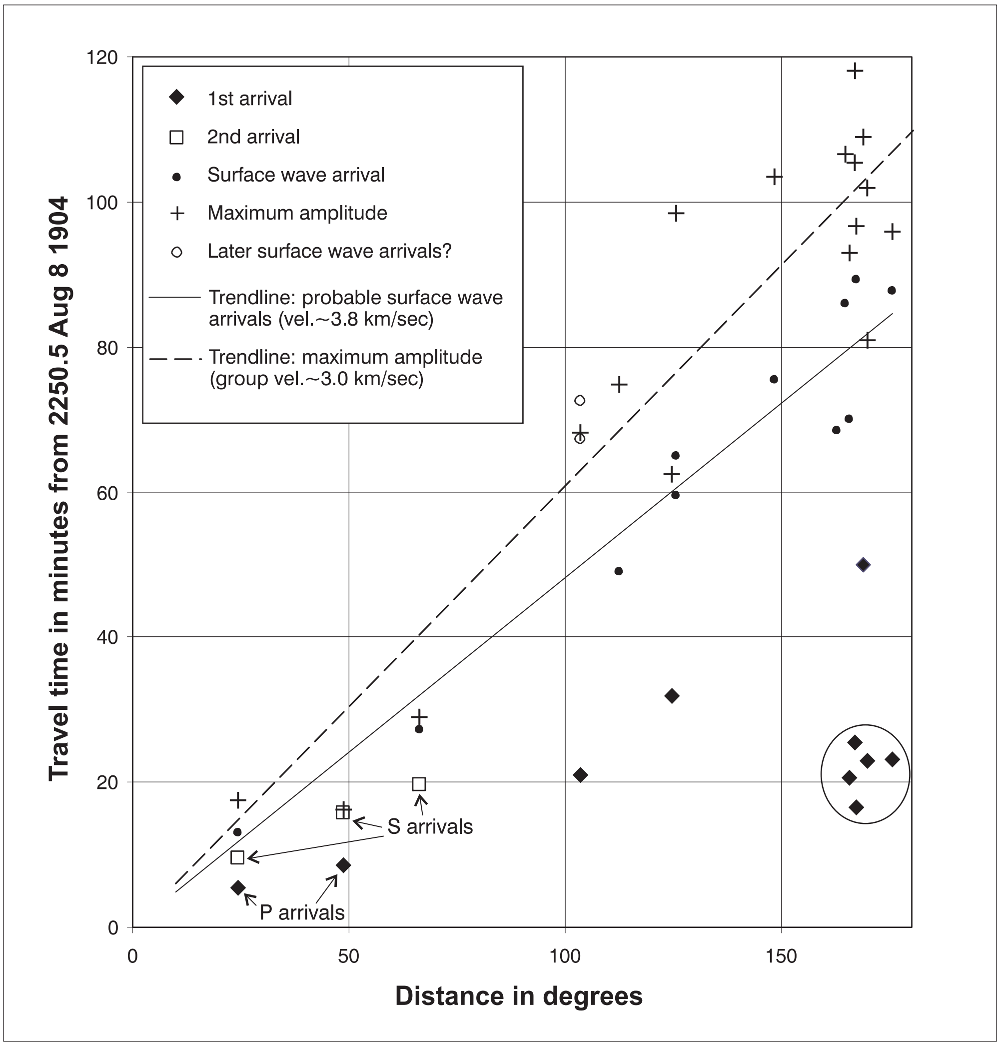

Figure 7: ***Plot showing the times of reported phase arrivals and maximum amplitude. Note good P and S arrivals at several stations, as well as reasonable PKP arrivals (circled) within 2 minutes of expected time. Best fit lines through the origin time and the probable surface wave arrival times and the maximum amplitude times are shown, respectively corresponding to velocities of 3.8 km/s and 3.0 km/s.***

At a location between Masterton and Mauriceville one eye-witness account records: "*Some settlers were out on the hills when the earthquake occurred had a unique experience, being able to see with the naked eye how the earthquake travelled. The first sign of it came from the north, Mauriceville way, and the falling of trees in that direction indicated some unusual event. Then the earthquake came sliding along to where they stood and almost lifted them off their feet... Then they watched the wave receding from them in the direction of Masterton. They could see successive stretches of land rising and falling, one after another, on the road to town, and by the time the monster reached Masterton, all was again calm and still. They heard the earthquake at Mauriceville, then felt it under their feet, and next saw it moving from them in successive waves of the ground towards Masterton*" (Wairarapa Daily Times 13 August 1904). This constrains the epicentre to north or north-east of Mauriceville.

The other eye-witness account from Umutaoroa records that: "*[he] saw the wave as it passed under the Piri-Piri Block some miles away. Trees surged in the air and crashed together; then as the wave advanced, he saw it rock the trees in the Mangatera Valley; while finally it reached where he was standing bringing down branches, and in some cases the trunks of dead trees in all directions.*" (Dannevirke Advocate, 10 August 1904). This constrains the epicentre to the east or a little south east of Dannevirke.

Taken together these descriptions fairly strongly imply a location east, or possibly a little south-east or north-east of Dannevirke. They exclude an epicentre further south towards Castlepoint (i.e. Smith & Berryman (1986) location). Taking into account the MM7 intensity at Dannevirke, an epicentre from about Weber to near Cape Turnagain is implied. This epicentre is consistent with the isoseismal map as well as observations from Porangahau, Wimbledon and Herbertville that the violent part of the earthquake (S-wave) followed very quickly after the first trembling (the P-wave), indicating the closeness of the earthquake's epicentre. The majority of directions from further afield were also remarkably consistent with an epicentre near Cape Turnagain, as were estimates of (what is now recognised as) the time between the P and S wave arrivals. The epicentre is, however, inconsistent with the perception of one person at Porangahau that the earthquake came from the east (Hill, 1904a).

The epicentre is here adopted as 40.4ºS 176.4ºE near the geographic centre of the highest intensity isoseismal. This location has a nominal error of 30 km.

FORESHOCKS AND AFTERSHOCKS

The occurrence of aftershocks is often an important indicator of the depth of the earthquake. Ideally, their distribution can also reveal information about the nature and extent of fault rupture. According to Hogben (1905), several foreshocks and 20 or more aftershocks occurred. However, dates and times are not given, and the Dominion Observatory's registers of earthquakes for this era are incomplete due to Hogben's temporary withdrawal from duties as Government seismologist because of illness (Roth 1952).

Other than the mainshock, Seismological Circulars (BAAS, 1905) and Dominion Observatory registers of earthquakes (GNS files) list only two instrumentally recorded earthquakes in August-September 1904 to be of East Coast origin — those on August 14 and August 24. Newspaper searching reveals three earthquakes were felt in the two weeks before the earthquake (Table 3). The two earthquakes listed above, and at least 18 others (corresponding to Hogben's 20 events), were felt at locations within the Masterton to East Cape area in the month following the mainshock (Table 3). The question is whether these events were aftershocks in the strictest sense, that is, earthquakes on or close to the mainshock fault plane rather than induced seismicity nearby.

The *New Zealand Times* of August 15 notes that small perturbations were recorded instrumentally on the Wellington Milne seismograph record for about 9 hours following the mainshock. Some of these perturbations can be seen in two hours of recording after the mainshock, shown in Figure 8a, on the only part of the 1904 earthquake record that is extant. The Wellington Milne seismograph record of the M_S6.9 1901 Cheviot earthquake (Dowrick & Rhoades, 1998) is also still extant, in GNS Science (GNS) files, and is shown in Figure 8b for comparison with the 1904 earthquake. The 1901 earthquake, centred some 200 km from Wellington, is known to have occurred at shallow depth within the upper crust (Dowrick, pers. comm.) with numerous felt aftershocks (GNS files). These are clear on the Wellington record as many small irregular sharp perturbations. The irregular nature of the mainshock trace also shows the contribution of aftershocks, a feature that appears to be absent in the 1904 mainshock, which decays relatively smoothly over 15-20 minutes as would be expected from an undamped instrument not excited by further events. The small perturbations after the mainshock on the 1904 record are not as sharp as those on the 1901 seismogram, are much less frequent, and more resemble surface waves from distant earthquakes rather than local shocks. However, it is probable that they represent small earthquakes and hence presumably, small aftershocks.

These small earthquakes, however, do not appear to have been felt in the highest intensity area where one would expect aftershocks to be most strongly felt. Letters from Herbertville, where the highest intensity was experienced, written within a day or two of the mainshock make no reference to aftershocks, either as small tremors or as large enough events to delay repairs or cause concern. Many newspapers make it clear that aftershocks were expected, but despite there being newspapers that regularly covered events at coastal settlements in the epicentral area, no earthquakes are noted as being felt there in the month following the mainshock. The *Dannevirke Advocate* (August 10) explicitly states that no other shocks were felt at Dannevirke, 40 km from the adopted epicentre, in the first day after the main event. Magnitude 4 and above earthquakes at depths of 45 km or less, had they occurred, would have been felt in the Dannevirke area, as well as in the areas east of Dannevirke (and therefore reported in the Dannevirke newspaper).

The only indication that earthquakes were felt in or near the highest intensity area is from one of Hill's correspondents, who writes one month after the August 9 mainshock, on September 8, that, "we [at Weber] are having on an average a shake every other day or night now. We had three in succession this morning at eight o'clock." (Hill 1904a). However, a very similar comment from one of Hill's other correspondents, at Mohaka, some 150 km from the epicentral region, *"During the following fortnight [after August 9] we experienced several slight shocks [at Mohaka] - in fact one almost every day - but none of them severe, - most being just slight tremors."* (Hill 1904a), suggests at least some earthquakes originated from sources other than Cape Turnagain. If any or all of the earthquakes felt at Mohaka were aftershocks, at least some parts of the coastal settlements north and south of Cape Turnagain should have strongly felt the earthquakes at intensities of MM6 or more, surely worthy of comment in local newspapers. Similarly, a series of earthquakes felt in Napier on August 19-20 with the accompanying comment, "Napier is still shaking" should have caused intensities of MM5 within the epicentral area, again surely worthy of comment.

More widely felt events, on August 14, which was given an East Coast origin (BAAS, 1905), and on September 8 can be shown to be distant from Cape Turnagain. The time between the P and S wave arrivals on instrumental records from Christchurch (Figure 8c) of the August 14 earthquake suggest an earthquake about 10º distant, which, given the felt effects, was almost certainly to the northeast of East Cape. The earthquake was apparently recorded in Wellington, but the seismograms no longer exist. It was recorded also in Perth and Melbourne, Australia. Taken together, these records and the reported felt intensities suggest a distant source earthquake with a magnitude of $M \geq 6.5$.

Although widely felt from Tolaga Bay to Wellington, and reported by Hill's Weber correspondent (Hill 1904a), the September 8 earthquake does not seem to have been recorded instrumentally, as Wellington and Christchurch registers of earthquakes do not list it. If it had been strongly felt in the Cape Turnagain area, it would almost certainly have been noted and given an east coast origin as the August 14 earthquake had been. The felt intensity distribution is most easily explained by a moderate magnitude earthquake occurring within the subducted plate beneath central North Island. The other event, given an East Coast origin and listed in BAAS (1905), on August 24, is reported felt at Pahiatua only, suggesting it was an isolated small local shock.

The only other earthquake that needs discussion is one that occurred within a few minutes, possibly within as little as one minute, of the mainshock. This earthquake cannot be distinguished as a separate event on the Wellington instrumental record. Its existence is clearly identified only in an account from the crew of a coastal ship, which was 100 km south of Cape Turnagain: "*First came a very heavy shock, lasting some time, variously estimated at from 10 to 20 seconds. It shook the ship just as though it had struck a rock, and frightened some of the crew into thinking that had actually happened, though the sea is about 2000 fathoms deep there. The heavy shock was quickly followed by a much lighter one…. No subsequent shocks were felt"* (*Timaru Herald* Aug 17). Other reports which suggest a second shock closely following the mainshock are from: Tolaga Bay ("first a severe shock, then quivering then a second (slighter) shock"); Waipatiki ("towards the end [of the violent part of the shock] there were two sharp violent shocks"); Pahiatua ("Three very pronounced earthquake shocks, preceded in each instance by earth tremors"); and Wanganui (two distinct shocks lasting 30 sec & 40 sec). These descriptions, however, could also be interpreted as various phase arrivals of the mainshock, or as sub-events within the mainshock, rather than a separate event, as can the descriptions of the intensity

Table 2. Earthquakes felt at locations between East Cape and southern Wairarapa in the fortnight before and month after the August 9 (NZT) mainshock.

Date and time NZT		Location(s) where felt	Comment	Source
Jul 23	0230	Wairoa	slight shock	WG Jul 26
Jul 23	0630	Wairoa	prolonged but not severe	PB HJul 23
		Wairoa	two shocks, two minutes apart	WG Jul 26
		Napier	heavy shock	PBH Jul 23
		Hastings	prolonged	PBH Jul 23
		Waipawa	felt	HBH Jul 25
Aug 08	evening	Onga Onga	slight	HL
Aug 09	0330	Feilding	sharp	RAMA Aug 9
Aug 09	**1020**	**MAINSHOCK**		
Aug 10	am	Feilding	slight	FS Aug 10
Aug 10	1600	Tolaga Bay	slight	HL
Aug 11	2120	East Cape Lighthouse	severe but no damage	MDF
Aug 11	ca. 2330	Tolaga Bay	felt	HL
Aug 14	1420	Waipawa	slight	EP Aug 15; DT Aug 16
		Napier	strongest of several slight shocks felt over the preceding few days; no alarm	WM Aug 16
		Gisborne	slight	PBH Aug 15
Aug 15	--	Waipawa	slight	WM Aug 16
Aug 19	0425	Taihape	sharp, lasting nearly half a minute	WDT Aug 20
Aug 19	1345	Napier	two sharp shocks; not felt at Gisborne; probable confusion with next event	PBH Aug 20
Aug 20	1340	Napier	two distinct shocks	WM Aug 20
Aug 20	2125	Napier	sharp; "Napier is still shaking."	PBH Aug 24
Aug 22	1400	Napier	two slight shocks	PBH Aug 24
Aug 24	0633	Masterton	felt	WDT Aug 24
		Wairere	sharp but short	WDT Aug 26
Aug 24	2145	Pahiatua	slight	EP Aug 25
Aug 25	2200	Mohaka	heavy shock	DA Aug 27
		Dannevirke	not felt	DA Aug 27
		Wairoa	Not felt	WG Aug 26
Aug 08	2330	Wairoa	nlight	WG Aug 30
Sep 08	ca. 0800	Weber	three in succession	HL
Sep 08	0938	Wairoa	sharp and prolonged; direction	WG Sept 9
		Feilding	slight	FS Sept 8
		Gisborne	slight	PBH Sept 8
		Hastings	slight	WM Sept 8
		Wanganui	slight	WM Sept 8
		Wellington	slight	WM Sept 8
		Pohui (Te Pohue)	"rather severe"; some alarm	HL
		Mohaka	slight	HL
		Tolaga Bay	sharp	HL

DA – Dannevirke Advocate; DT – Daily Telegraph; EP – Evening Post; FS – Fielding Star; HBH – Hawke's Bay Herald; HL - Hill Letters 1904; MDF – Marine Dept. Files held at GNS; PBH – Poverty Bay Herald; RAMA – Rangitikei Advocate & Manawatu Argus; WDT – Wairarapa Daily Times; WG – Wairoa Guardian; WM – Waipawa Mail.

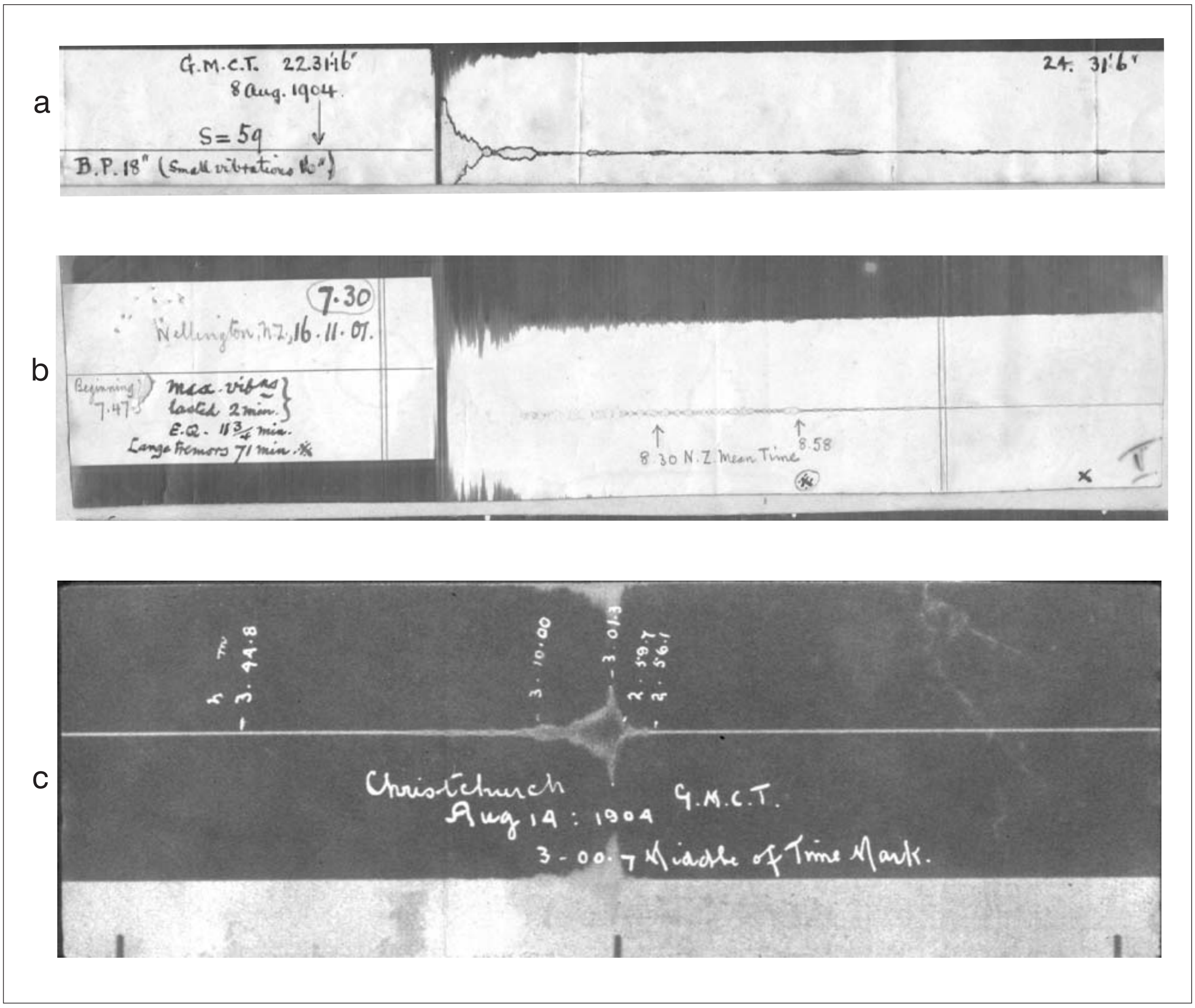

Figure 8: ***a). Wellington Milne seismograph record of the 1904 Cape Turnagain earthquake. Note that envelopes were drawn around parts of the trace in 1904. b). Wellington Milne seismograph record of the 1901 Cheviot earthquake. c). Christchurch Milne seismograph record of an earthquake on 1904 August 14. Note that the latter record reads from right to left.***

of shaking rising and falling several times over the duration of the mainshock at several other locations. There is no evidence, in the distribution of intensity, in the descriptive accounts of the mainshock in Wellington or the Wairarapa Valley, that this event was not an earthquake on the east coast. Hence, it was probably an aftershock. Further, there is no evidence of any other shock close to Wellington that might account for the shaking experienced there.

The evidence presented here suggests that the 1904 earthquake did not have many moderate or small magnitude aftershocks. Small earthquakes local to various areas of Hawke's Bay, deep or distant earthquakes seem to best explain most reports of shaking other than the mainshock, rather than aftershocks. Some local activity may represent a continuation of activity that existed before the mainshock or may represent induced seismicity in areas surrounding the mainshock rupture. For example, "loud and continuous rumblings" that were heard at Tikokino in late July (*Hawkes Bay Herald* Aug 03 1904), may have been small very local earthquakes. Such rumblings might also be heard in association with eruption of one of the central North Island volcanoes. The historical record indicates that Ngauruhoe was active in November 1904 (B. Scott, pers. comm.), but it is not known to have been active in August. Earthquakes felt at Otane on August 8, and at Feilding early in the morning of August 9, were probably unrelated to the later mainshock. There was also a long duration earthquake on July 23, strongly felt from Wairoa to Waipawa, but causing no damage. The reported occurrence of two shocks two minutes apart at Wairoa suggests this was a distant or deep event. Hence, contrary to Hogben's assertion of foreshocks, there is no evidence of these in the area of the mainshock.

AFTERSHOCK ACTIVITY AND IMPLICATIONS FOR FOCAL DEPTH

Since 1904, several relatively well-located large events have had epicentres near Cape Turnagain, and hence, we can compare their aftershock activity with that of the Cape Turnagain earthquake to gain insight into the depth of the 1904 event. For example, the epicentre of the 1904 event is located within 15 km of the epicentre of the 1934 M_W7.4 Pahiatua earthquake, which occurred in the overlying Australian Plate (Downes *et al*., 1999). Although the 1934 event had fewer aftershocks relative to other shallow historical events, aftershocks were frequent in the first few days after the mainshock (about 30 events $M_L \geq 3.5$ in the first 24 hours) (Downes *et al.*, 1999). Numerous small shakes were also felt in the epicentral area, the larger ones readily recognised 30 km away in Dannevirke. Similarly, the M_W6.4 1990 May 13 earthquake near Weber, which, like the 1934 Pahiatua earthquake, occurred in the overlying plate (Robinson, 1994), produced a rich aftershock sequence with 60 events with $M_L \geq 3.5$ within the first 24 hours (Downes *et al.*, 1999). Many of these were felt locally, and in Dannevirke 25 km away.

Events in the upper band of the double-banded seismicity typical of the subducted plate, such as the M_W6.2 (Webb & Anderson, 1998) earthquake near Weber February 19 1990, also seem to have numerous aftershocks (Robinson, 1994). However, Robinson cites several examples that suggest that events in the lower band have few aftershocks compared with the upper band. Further, events in the subducted mantle can also have few aftershocks. An example of one such event is the 1993 August 10 Ormond earthquake (near Gisborne), which initiated at 37 km depth, within the mantle of the subducted plate and was followed by aftershocks extending from near the base of the subducted crust to ca. 20 km into the mantle (Reyners *et al.,* 1998). Aftershocks in the mantle decayed exceptionally rapidly compared to those in the crust of the subducted plate above. Hence, the paucity of aftershocks in 1904 might be indicative of an event in the lower crust or mantle of the subducted plate.

There is, however, another possibility — that the 1904 earthquake ruptured the plate interface. The 1993 April 11 M_w5.6 (Webb & Anderson, 1998) M_W6.0 (Abercrombie & Benites, 1998) earthquake near Tikokino about 75 km north of the epicentre of the 1904 earthquake had extremely few felt or recorded aftershocks, with only two earthquakes with magnitudes $M_L \geq 2.9$ in the first two weeks after the mainshock. The location and mechanism of this event have been shown to be consistent with rupture on the subduction interface (Reyners *et al.*, 1997; Abercrombie & Benites, 1998). Reyners *et al.* (1997) suggest that the Tikokino earthquake initiated at an asperity on the plate interface, with rupture then propagating into subducted sediment lying in a conditionally stable field. Abercrombie & Benites (1998) suggest that subducted sediments surrounding the asperity, if present, might respond aseismically, and hence, produce few aftershocks. They also suggest that the rupture exhibited clear source directivity to the south, as does Reyners *et al.* (1997).

The 1958 M_S5.1 (Dowrick & Rhoades, 1998) [M_L6.1] Ashley Clinton earthquake, some 30 km closer to the 1904 epicentre, may also have been on the plate interface as aftershocks were almost completely absent (Reyners *et al.,* 1997). Webb & Anderson (1998) identify two other east coast events nearby to Cape Turnagain in the Havard CMT catalogue whose thrust mechanisms and depth are compatible with rupture on the plate interface — the 1980 July 3 and 1981 December 27 earthquakes, both with magnitudes M_W5.4. The first, located offshore, had 14 aftershocks ($M_L \geq 3.0$) within the first 24 hours, while the 1981 earthquake, located within 15 km south west of Cape Turnagain, had three aftershocks ($M_L \geq 3.0$) within the next month. However, the location and depth of these events are not well constrained.

Singh & Suárez (1988) have identified distinct regional variations in the number of aftershocks following large plate interface earthquakes. It has been found that parts of several subduction zones are characterised by sequences of low aftershock-producing large plate interface earthquakes (Singh & Suárez, 1988; Abercrombie & Benites, 1998). One of the most notable events with deficiency of aftershocks is the 1985 M_W8.1 Michoacán earthquake, well known for its devastating microzone effects in Mexico City over 300 km from the epicentre. This event, which produced only five aftershocks with $m_b \geq 5.0$, is one of several large historical earthquakes in the same region to have an aftershock deficiency (Singh & Suárez 1988). Singh & Suárez (1988) suggest that there is a correlation between the occurrence of these events, the strength of plate coupling, and the degree of heterogeneity present at the plate interface. Low-aftershock producing events tend to occur in moderately coupled zones which are characterised by moderate sized densely distributed asperities, one or several of which may rupture in major events. The moment release in the 1985 Michoacán earthquake, for example, was found to be confined to two distinct asperities, separated by about 80 km, that broke with a time separation of 26 s (Kisslinger, 1996), creating a long duration event.

According to Reyners (1998; 2000), the plate interface in southern Hawke's Bay is moderately coupled. Given this and the fact that at least one reasonably well identified aftershock-deficient plate interface earthquake (the Tikokino event) has occurred nearby, we can infer that the occurrence of other such events is plausible.

MAGNITUDE

Using joint calculation procedures, Dowrick & Rhoades (1998) obtain $M_S6.75 \pm 0.14$ for the 1904 Cape Turnagain earthquake using surface wave amplitudes from nine stations only. Dowrick & Rhoades' technique involves the calculation of station corrections for stations recording several New Zealand earthquakes from as early as 1901. Despite the paucity of data and relatively poor quality of instruments of the time, the magnitudes seem relatively robust. For example, the magnitude of the 1901 Cheviot earthquake, based on instrumental data of similar origin to the 1904 earthquake is reasonably consistent with its intensity data (Dowrick, pers. comm.).

Hence, with a view to identifying the more likely of the two possible scenarios for the 1904 earthquake, the observed isoseismal pattern and appropriate models calculated using the attenuation relationships of Dowrick & Rhoades (2005) were compared. In the first instance, two models compatible with the two possible sources of the 1904 earthquake were considered: an interface model with low dip angle reverse mechanism (similar to the 1993 Tikokino earthquake), and a high-angle dip main seismic region model (i.e. unspecified mechanism) at 40 km deep in the slab (the dip being similar to the 1993 Ormond earthquake (Reyners *et al.* 1998)).

Observed radii normal to the strike of the isoseismals (*b*) are reasonably close to the predicted radius dimensions, whether the earthquake occurred on the plate interface (Fig. 9a) or 40 km deep in the slab (Fig. 9b). The greatest difference between predicted and observed intensity is one intensity unit, which is within the scatter observed in the residuals for the main seismic region by Dowrick & Rhoades (2005), implying compatibility of the *b* axis radii with the instrumental magnitude.

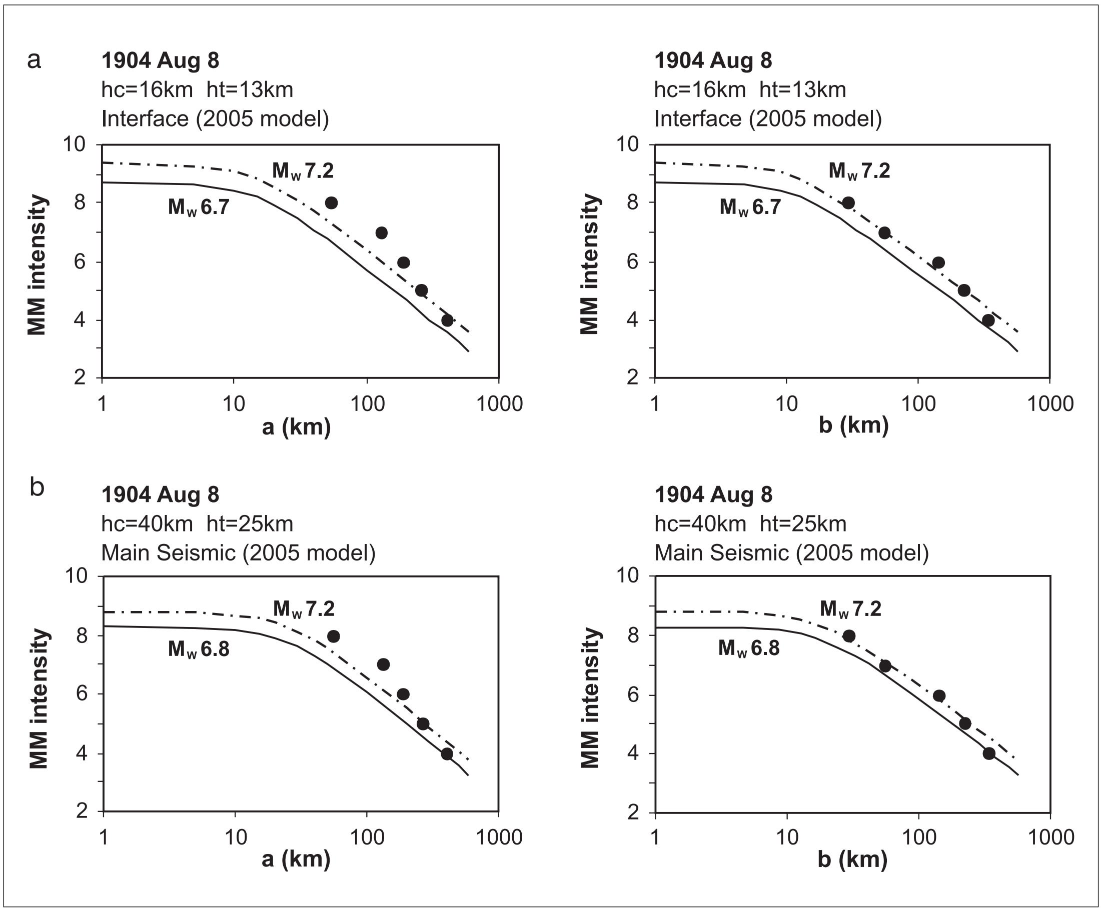

Figure 9: ***Plots of the a and b dimensions (a=semi-axis length along major axis of the isoseismal;b=semi-axis length along minor axis) for the 1904 earthquake and for Dowrick & Rhoades (2005) attenuation relations (curves) for***
a. M_W6.7 and M_W7.2 plate interface earthquakes at 16 km depth rupturing to 13 km depth,
b. M_W6.8 and M_W7.2 Main Seismic Region unspecified mechanism slab earthquakes at 40 km depth rupturing to 25 km depth.

In contrast, the observed radii in the direction of the strike of the isoseismals (*a*) are generally greater than the predicted dimensions for both interface and slab earthquakes (Figure 9). In the interface model, the greatest difference between predicted and observed intensity is two units. The misfit becomes more apparent when the radius dimensions are considered. For example, the observed MM7 and MM6 *a* radii, which are relatively well constrained, are 125 km and 185 km respectively, while the predicted radii are 43 km and 85 km. The misfit of the MM8 isoseismal is also large. However, the MM8 isoseismal is not so well constrained, and a dimension less than that drawn is possible. The fit of predicted and observed isoseismals for the main seismic region slab model is similarly poor. An improved fit that reduces the greatest residual in the intensities to close to one unit (i.e. a "best fit" is not attempted) is obtained with magnitudes of M_W7.1-7.2 (Figure 9 shows M_W7.2 only). The higher magnitudes increase the maximum predicted intensity for the interface model to MM9. While MM8-9 is the maximum intensity plotted on Figure 4, MM9 may have been reached near the epicentre (see description of damage at Herbertville in Appendix 1), but is not readily recognisable because of sparse population and lack of masonry.

Other models, in particular for the 40 km deep scenario, are possible, but those chosen are considered most plausible. Lower angle faults at 40 km deep were trialled, but the fit was poorer.

As there is variability in the fit of isoseismals from earthquake to earthquake, a perfect fit of observed to predicted isoseismals is not expected. For example, the residual standard deviation of the observed MM intensity to the Dowrick & Rhoades (2005) main seismic region model is about 0.45 units of MM intensity. Both of the models shown here indicate that the instrumentally determined magnitude is too low, or that the models inadequately represent the isoseismal pattern for this event. The latter is unlikely to be the case for slab events as the attenuation models were developed from 18 events, including an M_W7.0 event.

On the other hand, New Zealand has experienced few instrumentally well-determined large plate interface earthquakes (Doser & Webb, 2003), none along the Hikurangi margin, with which to determine attenuation relationships. Dowrick & Rhoades (2005) recommend that their interface model should be viewed with caution beyond the magnitude of the highest magnitude well-recognised earthquake in their database, an M_W6.8 in Fiordland. While their model, based on New Zealand interface earthquakes, is consistent with international observations that for smaller magnitude events intensities are about half a unit smaller than crustal or slab earthquakes of the same magnitude, mechanism, and source depth, international observations of PGAs (and by inference, intensity) are now indicating that the lowered intensity model may not hold true for larger magnitude earthquakes. This is consistent with the recent observation by McGinty (2004) that relations for PGA in use

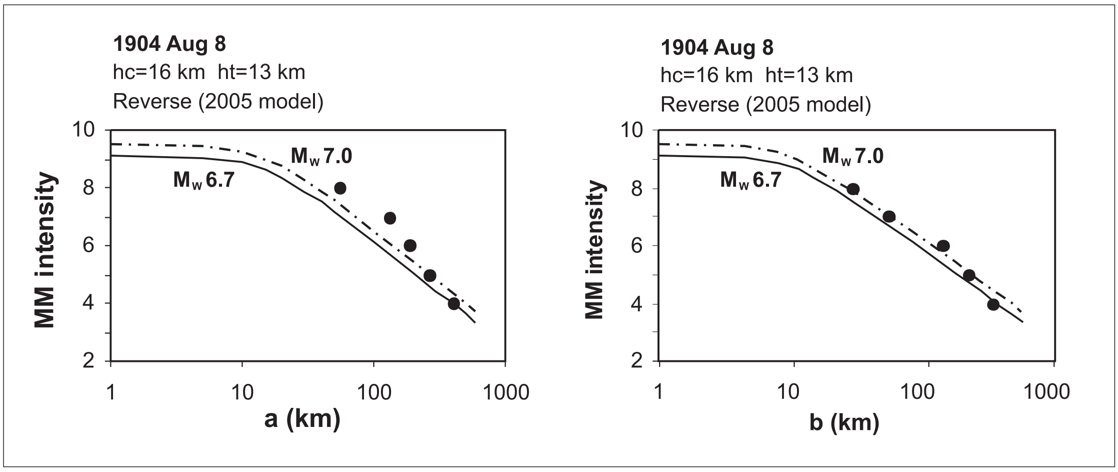

***Figure 10:** Plots a and b dimensions (a=semi-axis length along major axis of the isoseismal; b=semi-axis length along minor axis of the isoseismal) for the 1904 earthquake) and for Dowrick & Rhoades (2005) attenuation relations (curves) for M_W6.7 and M_W7.0 Main Seismic Region reverse mechanism earthquakes at 16 km depth rupturing to 13 km depth.*

in New Zealand for interface earthquakes (based on McVerry et al. 2000) generally under-predicted the PGAs recorded in the August 2003 M_W7.2 Fiordland earthquake, especially within about 200 km of the source, although they generally performed better for the aftershocks.

Hence, it is interesting to compare the fit of the observed isoseismal radii with a model for a low angle reverse fault at the same depth and with the same fault dip as the interface model (Figure 10), and to note that the fit is considerably better than that for the interface model, and that a magnitude of M_W7.0 produces an acceptable fit to the observed data (i.e. residuals reduced to about one intensity unit). For each of the models in Figures 9 and 10 the fit of the *b* radii improves at the higher magnitudes, but the fit at M_S6.75 is not unacceptable.

Hence, given the uncertainty in the validity of the interface model at higher magnitudes, it is not possible to use attenuation models to determine which depth and mechanism best characterises the 1904 earthquake and at the same time, unequivocally determine the magnitude.

A further complication in attempting to refine the magnitude is that focussing by high seismic velocity-contrast structures within the subducting slab, or the crust, particularly the base of the crust, or directivity of rupture could affect the distribution of intensity or indeed the instrumental magnitude.

For example, focussing by crustal structures was implicated in amplifying PGAs at sites in San Francisco, notably the Marina area, in the Loma Prieta earthquake (Somerville & Yoshimura, 1990). Using data from the 1990 Weber earthquake, Galea (1994) identifies a high velocity layer within the mantle between the earthquake epicentre (which is close to the 1904 epicentre) and Wellington that focussed P-wave energy at a location just south of Wellington. She further identifies some energetic features in the seismograms recorded to the north-east of Weber that could be attributed to a slow velocity layer on top of the subducted slab acting as a wave guide. Galea notes that the presence of these high- and low- velocity layers has been found by others, and that further research is needed to fully understand their possible focussing and wave-guide effects on S-wave as well as P-wave energy.

Higher PGAs and individual station magnitudes to the south of the 1993 M_W5.6 Tikokino earthquake (Abercrombie & Benites, 1998; Reyners *et al*., 1997) have been shown to be a result of strong directivity, caused by southwards unilateral rupture. Directivity of fault rupture might also be reflected at large distances in the distribution of surface wave magnitudes. For example, directivity may be reflected in the relative amplitudes of the surface waves R1 and R2 (or R3 vs R4) that propagate in opposite directions from the source. This effect is most visible at about 160-180° from the source, i.e. in Europe. While there is some suggestion in the data shown in Figure 7 that the maximum amplitudes occur very late for R1 and hence are compatible with R2 (i.e. rupture directed to the south), errors in times of other phase arrivals suggest that little reliance can be placed on these observations in the absence of original seismograms. Directivity might also be reflected in greater amplitudes (and magnitudes) at closer stations in the direction of rupture, with lesser amplitudes and magnitudes in the opposite direction. Hence, the lower magnitudes at US stations at Honolulu and Baltimore, and the Canadian stations at Victoria and Toronto might suggest rupture away from these stations. However, this evidence is not unequivocal, given the paucity and poor distribution of stations and the confusion of effects from directivity with the effect of convergence of surface waves at the antipodes causing high amplitudes and magnitudes. The station terms developed by Dowrick & Rhoades (1998; 2005) should also incorporate some of these effects.

DISCUSSION AND IMPLICATIONS FOR HAZARD ASSESSMENT

A combination of factors makes it difficult to give definitive parameters for the 1904 Cape Turnagain earthquake. It occurred at a time when instrumental records and seismological understanding were insufficient for seismologists of the time to determine an epicentre. The distribution, quantity and quality of the instrumental records may also be responsible for the discrepancy between the surface wave magnitude of M_S6.75 ± 0.14 and the higher magnitudes suggested by the intensity data, that is, at least M_W7.0 (low angle reverse fault at interface depth) and possibly as high as M_W7.2 (interface or slab). However, a magnitude up to M_W7.2 is not unreasonably higher than the instrumental M_S magnitude, and is within the scatter observed when M_W is plotted against M_S (see Figure 3 in Dowrick & Rhoades (1998)).

The distribution and interpretation of intensity data and more particularly, the detection of aftershocks, are hampered by the earthquake epicentre occurring in a relatively sparsely populated area. The possibility that isolated small aftershocks occurred, but were not consistently reported, cannot be excluded. However, the lack of reports of damage, or even concern, indicates that there was not a constant succession of small shocks immediately following the mainshock, and that there were few, possibly only one, moderate aftershocks. The only larger aftershock readily identified is one that occurred within a minute or two of the mainshock.

The paucity of aftershocks implies that the earthquake occurred either on the plate interface at about 16 km depth, or that it occurred in the lower seismicity band of the subducted slab or in the top of the mantle at about 40 km depth. Attenuation models cannot eliminate one of these locations on the basis of a misfit of the isoseismals.

Low numbers of aftershocks have been shown to be characteristic of certain subduction zones, or parts of subduction zones, and these zones show evidence of moderate coupling (Singh & Suárez 1998), as does the Cape Turnagain area (Reyners 1998, 2000). The Mexico subduction zone, where the low aftershock producing $M_W8.1$ Michoàcan earthquake occurred, is one of these zones. It is depicted as having moderate sized densely packed asperities, several of which rupture in major events, possibly with a long time separation, and hence, a long duration earthquake. These asperities are surrounded by sediments, which do not support the occurrence of aftershocks, and hence, allow little expansion of the aftershock zone. The question of importance for seismic hazard assessment is whether this represents the characteristics of the plate interface in southern Hawke's Bay, and whether the 1993 Tikokino earthquake and the 1904 earthquake characterise the type of plate interface events that might be expected in the area in the future. Other questions to consider are whether the presence of such a zone would limit rupture of the interface in the southern part of the North Island, allow rupture to continue northwards more slowly, aseismically, or with low slip on this section of the plate interface.

The pattern and extent of damage in Wellington, with some exceptions, is found to be reasonably consistent with the zone of sediment and fill delineated in the hazard maps of Wellington as having the potential to experience enhanced shaking. As no evidence of a second earthquake near to Wellington can be found, consideration has to be given to the MM6-7 damage in an otherwise MM5-6 area being a microzone effect from an earthquake centred 170 km away. No such effects are recorded in Wellington City in the closer and larger $M_W7.4$ 1934 Pahiatua earthquake (Downes et al. 1999), in which MM5-6 was experienced. However, Downes et al (1999) suggest that a small pocket of stronger shaking in Petone may be a result of enhancement. The 1934 earthquake was shallower than the 1904 earthquake, that is, within the overlying Australian Plate and it had a predominantly strike-slip mechanism. Focussing by sub-surface structures, or wave trapping within low velocity layers could provide a mechanism for enhancement of stronger shaking in isolated areas within zones of lesser shaking, such as occurred in the Marina area in the Loma Prieta earthquake, and the potential for these effects at Wellington from the east coast of the North Island perhaps deserves further investigation.

As far as can be determined from observational and instrumental data, the August 9 (August 8 at 2250.5 UT) 1904 $M_W7.0$-7.2 Cape Turnagain earthquake occurred at 40.4ºS 176.4ºE with a nominal estimated error of about 0.3º. It occurred either on the plate interface at about 16 km depth, or in the lower subducted plate or upper mantle at about 40 km. The higher magnitude now places the 1904 earthquake among the ten largest shallow earthquakes experienced in New Zealand in historical times.

At $M_W7.0$-7.2, the intensity distribution is acceptably close to that predicted from the attenuation models of Dowrick & Rhoades (2005) for an earthquake in the lower part of the descending slab and hence, the damage caused by this type of event should be of no surprise to hazard modellers. However, a magnitude of 7.2 is higher that the M_{cutoff} 7.0 adopted by Stirling et al (2000) for distributed seismicity at depths 14-42 km in this part of the east coast.

An event of the magnitude of the 1904 earthquake on the plate interface is not unexpected, an $M_{max}8.1$ (Berryman model) having been allowed for by Stirling et al (2000) for the Cape Turnagain area. Assuming the extent of the highest intensity isoseismal is representative of rupture length, the rupture length is compatible with their adopted segmentation of the interface.

If the 1904 earthquake was a large plate interface event, it is unique in our known seismic record for the east coast. Dowrick & Rhoades (2005) recognise that their models for interface earthquakes may not adequately represent the intensity distribution of earthquakes larger than $M_W7.0$. Their use may result in underestimation of the areal extent of damage. It is possible that the models of Dowrick & Rhoades (2005) for low-angle thrust events at interface depth may better represent the intensity distribution for large interface earthquakes.

Given the quality of the instrumental and observational records and the lack of modern analogies, it is doubtful that the 1904 Cape Turnagain earthquake can be better located or the depth better determined, thus exemplifying the difficulties in locating a large historical earthquake that has not left a visible trace on the landscape in the form of a surface fault rupture. Nevertheless, the study of this earthquake has some important implications for hazard assessment.

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APPENDIX 1: SUMMARY OF DESCRIPTIVE ACCOUNTS AND ASSIGNED INTENSITIES

Note that not all locations in Table 1 have individual entries, as newspaper accounts often combined information for a number of locations.

NORTH ISLAND

Akitio: "the recent earthquake played havoc with the chimneys throughout the [Pongaroa-Akitio] district". The chimney at Akitio Homestead went through the roof and Mr F. Armstrong's new residence [at Akitio] was reported as completely wrecked (no detail) and in need of rebuilding. **MM8?**

Apiti: little damage; one chimney damaged; a few leaky water tanks. **MM6**

At sea off Cape Palliser: The crew of the barque *Alma* felt a severe earthquake at sea at 41°37' S 176°50' E. "First came a very heavy shock, lasting some time, variously estimated at from 10 to 20 seconds. It shook the ship just as though it had struck a rock, and frightened some of the crew into thinking that had actually happened, though the sea is about 2000 fathoms deep there. The heavy shock was quickly followed by a much lighter one.... No subsequent shocks were felt."

Atiamuri: slight tremor. **MM3**

Auckland: very slight shock. **MM3**

Awahuri: at one large house, two chimneys broken off, a window fallen in and one side of the building strained. **MM6**

Ballance, Ngaturi, Makuri, Tane, Kaitawa, Mangatainoka, and Alfredton: many chimneys damaged or down; the burning down of a 12-room house at Tawataia attributed to chimney damage; crack 60 metres long opened in the side of the road in the Makuri Gorge. **MM7?**

Bideford: many chimneys fallen or cracked; general destruction of crockery; trees fallen; cracks formed in the ground. **MM7?**

Black Head: large slips from coastal cliffs.

Blackburn: difficult for people to walk steadily; nausea experienced; some chimneys damaged, twisted or fallen; some buildings damaged (no detail); limbs fallen from trees; some crockery and household goods broken. **MM6-7.**

Bramerton: (homestead) all chimneys fallen; greenhouses wrecked; windows broken; great damage to household items. **MM7?**

Brancepeth (a large station ten kilometres south of Taueru): all (48) chimneys damaged. **MM7?**

Bunnythorpe: a few chimneys cracked; no serious damage. **MM6.**

Cape Turnagain: large landslips from coastal cliffs

Carterton: much damage done to goods in shops, several chimneys damaged; several thousand pipes broken at the Brick Company. **MM6.**

Castlepoint and Whakataki: sand fountains; many fissures from ~2.5-4 cm wide extended several chains (20-60 m?); Whakataki stream "thick and disturbed" for a mile (1.6 km) upstream. At Whakataki Hotel: chimneys fallen and much damage to bottles, etc. **MM7?**

Clifton and Cape Kidnappers: Dust assumed to come from a large landlside at the end of Cape Kidnappers was seen rising for 10 minutes. Dust could be seen all along the beach from Clifton Station to Cape Kidnappers.

Clive: some chimneys partly demolished, others cracked. **MM7.**

Dannevirke (pop. 3,500, 720 dwell.): difficult for people to stand; nausea experienced; water splashed from gutters in High St.; many chimneys (domestic and non-domestic) badly cracked or fallen, many through roofs; many goods and ornaments thrown off shelves, pictures flung off walls in places; several brick walls thrown down in the main shopping area, others cracked with bricks loosened. The top two metres of the brick chimney stack at Haines's brick kiln fell and the kiln was so badly damaged as to require demolition. Many stacked pipes were also broken. A number of buildings were brick. Damage in the central shopping area was dominated by chimneys falling onto and through roofs. Many private wooden dwellings had their chimneys damaged and some shaken down, but the southern part of the town was reported to have suffered more than the northern part or that just west of the railway. Some chimneys were said to have had poor mortar. In two instances 2.5 cm pipes were broken, one near the Recreation Ground and the other at the base of the slope west of South School. At Tepapakuku, about two kilometres from Dannevirke on the Weber Road, considerable damage to a house and furniture (no detail given) was reported. In the same area near the Mangatera Stream cracks appeared trending along and across a small ridge running down to the stream, the author of the report suggesting the whole area was close to slumping or slipping. **MM7.**

Edenham, Omahu, Havelock, and Maraekakaho: chimneys cracked and fallen. **MM7.**

Eketahuna: alarm among residents; little damage; goods thrown about in shops. **MM5.**

Eltham: severest shock for years. **MM4.**

Featherston: several houses out of plumb; isolated breakage of pipes attached to water tanks; a few chimneys thrown over; much damage to goods in stores. **MM7?**

Feilding: several larger brick buildings cracked or out of plumb; parapet and top part of a brick wall in a new building collapsed; most brick buildings suffered little damage; several chimneys cracked; extensive breakages of crockery and glassware in the shops. **MM6-7.**

Foxton: heaviest earthquake in twenty years; some panic; a few, possibly many (different reports), chimneys damaged. **MM6?**

Frasertown: no chimneys overthrown; some water tanks cracked at the joints; water thrown from gutters of one house; cupboard doors swung; some clocks stopped; some ornaments thrown down; shaking nearly strong enough to throw people off their feet. **MM5-6.**

Gisborne: widely felt as prolonged and severe, with about thirty seconds of gentle rocking preceding violent shaking. A little plaster fell in one building (brick), slightly cracked in others; some chimneys damaged; many shop windows cracked; some crockery and glassware broken. Many buildings were not damaged, including the Harbour Board building which was under construction and had reached the second storey. **MM6.**

Gladstone: nearly all chimneys brought down; all bar stock at hotel destroyed; many other household articles broken; house on the hill above the river "completely wrecked" and feared unsafe to live in, its chimneys all brought down. Great quantities of earth fell from the cliffs near the Makaha Stream; sand fountaining occurred on the Ruamahanga River flats below the cliffs as well as a rent 250 m long near the approaches to the Ruamahanga bridge, the bridge itself apparently not suffering any damage. Three kilometres to the south, Glenside suffered four broken double chimneys and "everything breakable" smashed, while at an old house only 200 m distant, little damage was done. **MM8.**

Greytown: chimneys fallen or severely shaken; great quantity of crockery broken. **MM7.**

Hamilton: slight shock. **MM3.**

Hastings: felt by all, some people alarmed. Strong shaking for about 1-1.5 minutes with vibration being felt for a further three minutes. Strong shaking (S wave) was preceded by 15-20 seconds of lighter shaking (P wave). Most chimneys cracked or twisted, with some down; some bricks dislodged; little or no structural damage to buildings or brick walls; two shop windows broken; considerable damage to household crockery and stock in shops; water sloshed from tanks; telegraph and telephone wires intertwined. "Many water pipes were burst and the water service was disorganised." (Hawkes Bay Herald, Aug 10) Note that this was not reported elsewhere and in comparison with the other damage seems a little extreme if it refers to underground pipes but is reasonable if it refers to domestic water pipes and tanks. **MM7.**

Hawera: Post Office tower swayed; telegraph poles swayed, causing the wires to rattle; Town Clock stopped; small cracks were observed in the Post Office plaster and in one chimney only. **MM5.**

Herbertville (previously known as Wainui): people thrown off their feet; the only brick house "almost a total wreck"; 42 out of 45 chimneys in the settlement either levelled to the ground or broken off at or just below roof level; most water tanks burst; most breakables in houses smashed; large cracks formed on the river banks; hundreds of sand fountains, from less than a metre to over 6 metres in diameter, formed along the beach; numerous landslides in surrounding hills. **MM8-9, possibly MM9.**

Kurupuni and East Masterton: the damage less than in Masterton, no chimneys fallen; little damage in the shops. **MM6?**

Lake Rotomahana: "pretty severely felt ...at the scene of the Tarawera eruption" (probably an exaggeration related to seiche rather than strong shaking); seiche generated in the lake, "The water suddenly rose two feet, and a considerable commotion was also observed in the centre of the lake", and "There was a violent commotion on the water at Lake Rotomahana and the guide in charge of the boats had his hand badly injured endeavouring to hold the boat against the jetty." **MM4?**

Levin: considerable loss of crockery and other fragile goods in some shops; Post Office clocks stopped; fissures formed in the ground in some parts in the area. **MM5.**

Longbush: chimneys fell; some tanks damaged. **MM7?**

Manaia: some heavy objects displaced; lamps swung for a long time; no serious damage. **MM5.**

Mangahao: one house "canted at an angle", ie thrown from its piles? **MM7-8?**

Mangatarata: Mr de Pelichet's house "very much strained" and all chimneys wrecked. **MM7-8.**

Marton: prolonged and severe shock**. MM5?**

Masterton: The damage in Masterton district varied considerably from place to place. Some who were "actively engaged" did not notice the earthquake, while others panicked and ran into the streets. Many chimneys in the main part of town were damaged, some split, some twisted, others hanging and many completely levelled; some parapets cracked; some brick walls cracked and out of plumb; much damage done to goods in the shops and stores; Post Office tower was damaged, a portion of the concrete from the corner (about 1 kilogram in weight) falling to the pavement as well as cement being shaken out of joints and cracks formed in the brickwork; minor cracks in one or two other brick buildings; telegraph and telephone wires became intertwined. Towards the railway station, most chimneys were brought down. **MM7.**

Mauriceville: much damage to chimneys and crockery, Mauriceville East suffering more than Mauriceville West; trees, possibly dead from previous burn-off brought down; a new house (a few kilometres to the east of Mauriceville) thrown out of plumb, a piano thrown over and the chimney brought down. Several other houses suffered similar damage. Railway bridge damaged (no detail). MM7; Mauriceville East **MM8.**

Mohaka: severely felt; chimneys cracked (number not stated); bottles, vases etc. thrown from shelves; shaking and swaying of trees very pronounced; a narrow crack (1cm wide, 3-4 m long) in outer edge of the main road on the shingle hill leading from the Maori Pa to the Bridge. **MM6.**

Further, it was reported that. "Two men who happened to be on the beach, inform me that they saw a very large wave approaching the shore. They were unable to state size of wave - and explain that they were not frightened - 'but simply left'".

Morere: generally felt, books thrown off shelves in one house and outside standing pools of water seen to move. **MM5.**

Napier: Most severe earthquake since 1863[2], felt by all, one estimate of the duration of strong shaking being about two minutes. The strong shaking was followed by a strong "wave-like motion". A large number of chimneys were brought down, Colenso Hill noted as being particularly badly affected; hundreds of other chimneys twisted or badly cracked; some tall chimneys, viz. at the gasworks, waterworks, the White Swan Brewery and Robjohn's Brewery were undamaged. The walls of several brick buildings were "severely strained", some tops of parapets cracked and displaced, bricks fallen and there was much damage to crockery. Little damage was done to the Cathedral, ("The slight damage referred to is to the apex of the main gable of the south transept, which has been slightly shaken by the working of the roof timbers. This, the architects recommend, should be rebuilt for a height of 6ft."). Some shop windows were broken. There was a slip from the Bluff of several tonnes during the earthquake and other smaller slips occurred up to three days later. At Port Ahuriri, as well as the toppling of goods in storage, a crack up to 1cm wide appeared in the breastwork from Dalgety's store to Murray, Roberts & Co. There were also small cracks in the cement facing of the sea wall. The water at the Bluff Hill reservoir sloshed, the indicator registering a rise of more than 7.5cm in the water level followed by a fall of the same amount. Sand fountains at Whare-o-Maraenui, near the Tutaekuri River, and along the Tutaekuri River from the Meanee-Napier bridge to the Napier-Taradale bridge. **MM7.**

New Plymouth: severe and prolonged; no damage. **MM4.**

Ngapaeruru, Weber, Titree Point, Waipatiki and Waione: Within the 10-20 km that these places encompass: many

2 The 1863 earthquake is reported to have brought down many chimneys in the new settlement of Napier and to have caused a great crack or rift in the Takapau - Waipawa - Te Aute area. Several references to it have been sighted in researching the 1904 event but the location of the rift varies within the above area. It is reported also to have changed the course of the Waipawa River, but this may be confused with a devastating flood a few years later in which the course of the river was apparently altered and flowed onto Te Aute College lands. After twenty years, Te Aute College finally achieved its diversion again from their lands by the building of embankments. The area was said to have shaken constantly for many weeks (Downes, unpubl. data).

chimneys came down, some wrecked to their foundations, some coming through the roof; water tanks burst; heavy furniture moved; general breakage of crockery and ornaments, some places, dependent on location, little or no damage; one house near Weber severely cracked and out of plumb, and the iron torn from the rafters; little structural damage elsewhere; many old trees lost their limbs; some trees brought down; possible landslide near summit of Puketoi Range neart Oporae; many cracks formed, up to 20m long and 10cm wide on the Mangatoro Estate; several other cracks formed, one about 200 m long, in the road near the Akitio River at Weber; many other cracks in the 'back' country; possible ridge renting near *Oceanview* on Franklin Rd; bridge over the Akitio River near Weber subsided 30 cm; water in the river made muddy and the banks collapsed. **MM7-8.**

Norsewood: damage to isolated chimneys only. **MM6.**

Onga Onga: at least 20 chimneys down; nausea experienced; some water tanks broken. **MM7.**

Opunake: severe and prolonged; no damage. **MM4.**

Ormondville: few chimneys left standing. **MM8.**

Orua Wharo homestead, Takapau: all chimneys fell, much damage done by plaster falling in at least four rooms; many vases, ornaments and bottles thrown down; several windows broken; some heavy furniture overthrown; outside water tank burst seams; difficult for people to stand without holding on to door frames The walls required repapering (racked frame?). The likely cost of the repairs was estimated by S. Johnstone to be 2000 pounds. *Ashcott* and *Sherwood* homesteads were less damaged. **MM7-8.**

Otaki: slight damage (no detail). **MM5?**

Otane, Patangata: many chimneys cracked and fallen; sand boils in the nearby district (no detail); sand boils in the old Waipawa River bed between Otane and Patangata. **MM7.**

Pahiatua: felt by all; little damage; isolated damage to articles in shops; one or two chimneys damaged. Another report indicates cracks were caused in brickwork in several buildings. **MM6.**

Palmerston North: people ran into the streets; clocks stopped; some china and glassware broken; telegraph poles and trees swayed. On the Manawatu River, waves were thrown up on the shingle banks. **MM6.**

Patea: severe and prolonged; no damage. **MM4.**

Petone and Hutt Valley: goods upset; some chimneys broken, but few fallen; no damage to a new brick building in Jackson Street, Petone; a few plate glass windows broken; one or two old wooden buildings in Petone out of plumb. **MM6.**

Pohangina: a few chimneys cracked; some thrown down; goods thrown down in shops; one or two heavy slips on the river terrace. **MM6.**

Pongaroa: "the recent earthquake played havoc with the chimneys throughout the [Pongaroa-Akitio] district". The chimney at Akitio Homestead went through the roof and Mr F. Armstrong's new residence [at Akitio] was reported as completely wrecked and in need of rebuilding. **MM8?**

Porangahau: widespread damage; only three chimneys left standing; water tanks damaged; general destruction of household ornaments and crockery; some houses and the hotel severely damaged (no detail); impossible for people to stand unsupported; ground appeared to move in waves; a tank "was lifted bodily from the stand"; seiching and agitation in river with water splashing up on banks; river banks collapsed in several places, 50 m long crack in sand near river; possibly some sand-boils in nearby creek; a spring near town stopped flowing; small slides in the road cutting above the town. Houses down near the river said to have suffered more severely than those on the higher slopes. The quicksands on the beach between Porangahau and Blackhead were said to have been redistributed, and consequently dangerous. **MM8.**

Puketapu: several chimneys down; a tank burst in the hotel. **MM6.**

Rangitumau: House on hill undamaged, while nearby house on flat lost all chimneys and many household articles were damaged. **MM6-7.**

Rotorua: "merely noticed". **MM3.**

Ruataniwha Plains: briefly mentioned as similarly damaged as surrounding districts.

Shannon: Not severe. **MM5?**

Station homestead *Fairfield*: all chimneys badly damaged. **MM7?**

Station homestead *Springhill*: dead trees brought down.

Stratford: prolonged and severe shock. **MM4.**

Taihape: severe; causing some alarm but no damage. **MM4.**

Takapau - Ormondville: The approaches to the Kopua railway viaduct subsided to such an extent that the line was temporarily closed. (A potential disaster was probably averted by a very quick thinking railway ganger who, without specific instruction, performed an unscheduled second check of the line after the earthquake and signalled the train to stop.)

Taradale, Greenmeadows: many chimneys twisted, cracked or fallen; extensive damage to shop goods and household articles; hundreds of tonnes of metal fell at Redclyffe quarry near Taradale; sand fountains in Taradale. An artesian well stopped flowing on a property. **MM7.**

Taueru (Tauweru): people and animals thrown off their feet; total or partial destruction of chimneys in all except one house; doors 'sprung'; "one building was almost split in twain"; bridge abutment piers damaged, the cap of one being completely crushed and "the heavy timber wing strained"; many fissures in the road; rocks and boulders, up to 1m diameter, rolled downhill; some small landslides. One house said to have burnt down as the result of chimney damage. **MM8.**

Taupo: more severe than at Rotorua. **MM4?**

Tauranga: severe. **MM4?**

Tawa Flat: forcibly felt, but no "serious damage". **MM6.**

Te Aroha: not felt; the springs were reported to have stopped flowing for about quarter of an hour at the time of the earthquake.

Te Aute: a large gap formed in the road between Te Aute and Te Hauke; telegraph communication was cut in the same area. Chimneys (no detail) from Waipawa to Te Aute fallen.

Te Marua (called Mungaroa in 1904): chimneys of the school and teacher's house shaken down. **MM7?**

Te Pohue, Taupo Line: (close to what is now known as Te Pohue, on the Napier- Taupo road; in 1904 there was a small two storey wooden hotel near to the lake edge.) At least three chimneys badly cracked; several earth cracks, 3-5 cm wide. **MM6.**

Tikokino: difficult for people to stand; large trees bent and swayed; some chimneys cracked or brought down; much damage of goods in stores; heavy sawmill machinery and furniture was shifted; water emptied from containers and tanks; water in the creek rose and fell. **MM7.**

Tinui: all chimneys fallen; some furniture broken; school blackboards and books thrown about; window broken. **MM7-8.**

Tolaga Bay: no damage reported, other than two slips on a ridge leading to the north side of bay. Described as first a severe shock, then quivering followed by a second slighter shock. **MM4.**

Umutaoroa: difficult to stand, many chimneys damaged and fallen; dead trees brought down or limbs broken off. **MM7.**

Upper Hutt: crockery and glassware broken in most houses; many broken or fallen chimneys. At Silverstream Brick Works a high chimney was so badly cracked that it needed rebuilding. **MM7.**

Waimangu: "merely noticed". **MM3.**

Waipawa: of long duration, a feeling of sea-sickness common; some people thrown down; extensive damage to crockery and goods in shops; several shop windows broken; many chimneys in the area damaged, twisted or brought down (one estimate, 33% damaged); water tanks twisted and damaged, some burst. The Empire Hotel, a large two storey wooden structure, was badly damaged with two chimneys coming down, one crashing through the balcony causing it to fall. There were also extensive falls of plaster. One newspaper commented that the west end of town suffered little damage. The shingle of the river was observed to rise and fall and the river was made turbid. **MM7.**

Waipiro Bay: prolonged; no mention of damage. **MM4.**

Waipukurau: at least 50% chimneys damaged, a large number of these partly fallen down. A later report (Sept 20) states that upon inspection all chimneys had sustained some damage, which had not been obvious immediately after the earthquake. **MM7.**

Wairere: difficult for people to stand without holding on; many chimneys brought down; many water tanks wrecked or at least torn from their fastenings; much damage to crockery and pantry items; hundreds of large old (burnt) trees uprooted, or branches broken off. **MM7.**

Wairoa: severe and prolonged; small articles in shops thrown down; trees visibly rocked. **MM5.**

Wakarara: difficult for people to stand; nausea experienced; water in buckets and tanks thrown out; limbs of (possibly dead) trees were broken off. **MM6-7.**

Wanganui: people ran into the streets; a few chimneys damaged, slight damage in some shops and dwellings (no details); steamer at the wharf quivered; water thrown out of containers; water in the river near the Railway Bridge agitated and was measured as having sloshed 7-10 cm. **MM6.**

Wanstead area: nearly all chimneys from Herbertville to Wanstead badly damaged; chimneys at *Lake Station* fell. One large residence was burnt down as the result of chimney collapse. **MM8.**

Waverley: two chimneys shaken down; some crockery broken. **MM6.**

Wellington City: It is clear that the damage in the city area was quite variable, from strongly felt with no damage (MM5) in Brooklyn (a new hill suburb at the time) to MM7 in parts of the Central Business District, along Tinakori Road and Newtown In the most strongly shaken areas, there was considerable stock damage, many to most chimneys fell, many parapets and gables fell or were damaged, brick walls were cracked and windows broken. Appendix 2 details known building damage. **MM5-MM7.**

Weraiti: all chimneys down; much damage to glassware, etc. **MM7?**

Whanawhana: heavy shock. **MM5?**

***Whangaehu Station* (between Porangahau and Herbertville):** widespread, severe damage; all chimneys down; all tanks wrecked. It was also reported that "one of the fences was considerably damaged, the wires being broken, and the greater number of the posts forced out of the perpendicular." This was probably the result of slumping but was sufficiently unusual to warrant special mention in one of the letters to Hill. **MM8.**

Whareama: many chimneys fell; brick house at *Langdale Stn* so badly cracked that it was demolished; much crockery and ornament damage; heavy furniture moved and smashed in some cases. **MM7-8.**

Wimbledon (also known as Upper Wainui): many, possibly most, outside water tanks damage; almost all chimneys fallen, or cracked; at least one domestic window broken; heavy furniture moved or overturned; great destruction of pantry goods and crockery, vases, books, etc.; cracks, up to 5 cm wide, formed in the bed of Coal Creek (also known as McHales) Creek near Wimbledon; small landslides and slumping along the Wimbledon - Weber Road; numerous small landslides in the nearby hills; many dead trees brought down, especially near Taputahi (Taputahi is the local name for Te Awaputahi, the highest point between Porangahau and Wimbledon.). The largest landslide was near the top of Sergeant's Hill, a slump about 40-50 metres long sinking about 15cm below the edge of the road extending to a creek, 300 metres below. On Morgan's Slip (Wimbledon) many logs rolled downhill but some were thrown uphill about a metre, above beds in which they had been lying for years. One comment suggests the damage in Wimbledon was less than at Herbertville, Ti-Tree or between Weber and Dannevirke. **MM8.**

Woodville: felt by all, nausea experienced by some; several chimneys cracked, only one with its top knocked off; one or two shop windows broken ; minor damage to crockery, ornaments and bottles; some interior plaster falls in one building. **MM6.**

SOUTH ISLAND

Akaroa: slight. **MM3.**

Ashburton: slight. **MM3.**

Blenheim: prolonged. **MM4.**

Christchurch: felt. **MM4.**

Collingwood: sharp; windows and doors shaken violently; no damage; duration 1.5 minutes. **MM4.**

Greymouth: very severe; buildings swayed and rattled. **MM4.**

Havelock: strongly felt; no serious damage done. **MM5.**

Hokitika: smart; long duration. **MM4.**

Lyttelton: slight; windows rattled. **MM4.**

Nelson: prolonged; chimneys rocked; crockery rattled; no damage. **MM4.**

Queenstown: slight. **MM3.**

Reefton: two distinct shocks (3 s and 5-10 s); no damage. **MM4.**

Sumner: slight; windows rattled. **MM4.**

Timaru: very slight; felt by a few only. **MM3.**

Waimea Plains: not severe enough to cause damage. **MM4.**

Wakapuaka: sharp. **MM4.**

Westport: prolonged. **MM4.**

APPENDIX 2

Details of the damage done to Wellington buildings at the time of the 1904 Cape Turnagain earthquake.

Owner or occupier	Location	Use and building type (if known)	Description of damage	Intensity
	Brooklyn	Residential suburb	No damage	MM5?
	Brougham St., Mt Victoria	Mixed residential/business street	Many chimneys down	MM7
	College St.	Residential street	Many chimneys down	MM7
	Cuba St.	Mixed residential/business	Several plate glass windows broken	MM5
	Ellis St. (Ellice St., Mt Victoria?)	Residential street	Many chimneys down	MM7
	District including Hopper St.; Taranaki St., Broadway Tce., mostly res..	Mostly residential	Many chimneys down	MM6-7
	Jervois Quay	Warehouses	Superficial cracks in some buildings	MM6
	Kent Tce.	Mixed business/residential	Many chimneys down	MM7
	Newtown	Mixed residential/business Suburb	Many broken windows and collapsed chimneys	MM7
	Tinakori Rd.	Residential street	Several chimneys toppled	MM6
	District about Webb St., Nairn St., Upper Willis St.	Mostly residential	One or two chimneys down	MM6
Academy of Fine Arts	Whitmore St.	Gallery, simple construction, brick walls & iron roof	Plaster off walls; cracks at wood/brick joints; southern wall worst	MM6
Anderson	Willis St.	Crockery shop	Extensive stock damage, £30-40	MM6
Benjamin, D. & Co.	Jervois Quay	Importers	Goods thrown about; some damage	MM6
Callaghan, J. J.	Adelaide Rd.	Confectionery shop	Bottles fallen off shelves	MM5-6
Corporation Offices	Customhouse Quay	Offices	Cracking of interior walls on upper storey; roof damaged by bricks from neighbouring building	MM6?
Corporation Powerhouse	?		No damage to large chimney	MM5?
Customhouse	Customhouse Quay	Under construction	No damage	MM5?
Destructor	Cnr Herd St/Oriental Parade	large chimney	No damage	MM5?
Dunbar Sloane	Lambton Quay	Chemist	Some stock damage <£50	MM5-6
Education Board Building (near Library)	Mercer St.?	Offices	Pediment cracked in two places and plaster fallen from it	MM6
Electrical syndicate	?		No damage to large chimney	MM5?
Fielder, H.	Manners St.	Furniture shop	£120 worth of damage	MM6
General Post Office	Customhouse Quay		Small amount of cracked interior plaster; clock stopped; one door jammed	MM6

Government Buildings	Opposite Parliament	Large 2-storey wooden building	Some plaster down; some gaps between walls and partitions; some articles upset	MM6
Government House	Near Parliament?		Several small cracks in plastered ceilings	MM5?
Govt. Life Insurance Building	Customhouse Quay	Offices	Portion of parapets and tower (Oamaru stone & brick) fell; some bricks loosened; tower required rebuilding; some interior damage	MM7
Harbour Board Building	off Jervois Quay		Cracks from upper curve of ground floor window to roof near Tolls office	MM7?
Harrison & Co.	Kent Tce.	Pickle factory	£50-60 damage, bottles broken	MM6
Hayman & Co.	Victoria St.	Importers	Glassware etc thrown down, more on southern than northern wall	MM6
Haynes, C	Molesworth St.	New brick building	Plaster cracked	MM6
Innes; Fear, F.;Edwin, Arnold	Willis St.	3 shops in row	3 old chimneys toppled	MM6
Jackson & Co.	Jervois Quay	Paint (and glass?) merchant	Large quantity of plate glass broken	MM6
Kempthorne, Prosser & Co.	Upper Willis St. (temporary premises)	Wholesale druggists & manufacturing chemists	Hundreds of bottles fallen off shelves, much damage to stock	MM6
Kempthorne, Prosser & Co.	Willeston St.	Burnt out building under reconstruction	Some brickwork shaken off parapet on cnr. Victoria/Willeston St.	MM6-7
Law Courts			Fire buckets spilled water; some articles fell	MM6
M shed	near Harbour Board, Queen's Wharf?	Brick building	Crack in brick wall from roof to floor	MM7
MacKenzie, Dr. F. W.	Upper Willis St.	Brick residence	House bulged on one side	MM7?
Martin	Manners St.	Glass merchant	large quantity of plate & other glass broken	MM6
Mee, G.	Lambton Quay	Chemist	Some stock damage <£50	MM6
Mills & Co.	Aurora Tce.	Ironmongers warehouse	piles of ranges on upper floor collapsed & broken	MM6
Mr Corneal	Courtenay Pl.	Barber	Vertical crack in wall of upper storey; wide cracks in boundary wall	MM7
Myers & Co.	Lower Hunter St.	Glass & crockery merchants	Heavy stock damage (>£50); building slightly damaged (no detail given)	MM6?
Parker, W.	Manners St.	Wholesale chemist	Some stock damage <£50; some broken bottles	MM6
Parliament Buildings (new)	Lambton Quay/ Bowen St.		Several books off shelves; many interior plaster cracks; water in half-full fire buckets spilled; cracks in chimney	MM6
Phoenix Aerated Water Co.	St. Hill St.		Stock damage £50	MM6
Prof. Easterfield's Laboratories, Technical School	Kelburn Pde??	Laboratories	Some stock damage	MM5-6

Railway offices	??	New offices	Superficial minor cracks	MM6
Scott & Co.	Victoria St.	Glass- & crockery-ware	Some stock damage	MM5-6
Skating Rink	Vivian St.	Large wood & iron building,	Slight damage to joists in one room; some skaters did not feel shock; skates fell from racks	MM6
Smith & Smith	Victoria St.	Glaziers & colour merchants	Stacked plate glass & other glass smashed, £800 ?(Ev. Post) or £200? (NZ Mail)	MM6
Stewart Timber, Glass & Hardware Co.	Courtenay Pl.	Glass & timber merchants	Southern wall of building leaning several inches; cracks in concrete facade; some stock damage	MM6-7
Taylor, E. T.	Courtenay Pl.	Wine & spirit merchant	Damage to stock (dozens of bottles)	MM6
Te Aro House	Courtenay Pl., southern side	Large general store	Some damage to plaster	MM6
Thorndon School		Only brick school in Wellington	No damage	MM5?
Town Hall	Mercer St.	New building with "patent steel" ceilings	No damage	MM5
Turnbull, Hickson & Gooder	cnr Jervois Quay & Harris St.	Printers	Building badly cracked in three places between parapet & tops of windows	MM7
Union Steam Ship Co.	Customhouse Quay	Offices	Ceilings upstairs extensively cracked and displaced; many articles fallen & broken	MM6
Upper Willis St.	Upper Willis St.	Mostly residential street	Little structural damage to wooden houses but collapsed or damaged chimneys common; articles thrown off shelves	MM6-7
Wellington Public Library	Victoria St.	Brick building on "floating" foundation, built about 1892. Tower repaired after slight damage in earthquake in 1890's	Small pediment on Victoria St. fell; large pediment (0.5 tonne plaster & concrete) on Mercer St. fell; side of building out of plumb; on upper floor; books off shelves; ceiling & walls cracked. Estimated cost of repairs £750	MM7
Wellington Woollen Co.	Jervois Quay		Chimney pot fallen through roof	MM6
Willis St. School	Willis St.	Not brick	Clock stopped, some plaster fell	MM6
Wilton, G. W.	Cuba St.	Chemist	Heavy stock damage, >£50	MM6
Working Mens Club	Victoria St.		Plaster fall; broad crack in wall of upper storey	MM6-7

APPENDIX 3: DESCRIPTIVE ACCOUNTS OF WELL-DEFINED LIQUEFACTION

NAPIER: "Similar manifestations [to that seen at Patangata] were seen by me a few days later along the left bank of the Tutaekuri River from the Meanee-Napier bridge to the Napier-Taradale bridge." (Hill, 1904b)

"The shake was felt very severely on the reclaimed land on the Whare-o-Maraenui. Cracks appeared in several places, fine silt or gravel exuding and covering considerable patches of ground." (Hawke's Bay Herald, Aug 10 1904)

"A gentleman who was driving along the beach road at the time of the disturbance, and was close to the town boundary, happened to look over to the Whare-o-Maraenui reserve, and states that he saw quantities of mud thrown 10ft into the air in several places" (Hawke's Bay Herald, Aug 10 1904)

"I have heard that at Taradale cracks were formed which exuded fine silt or gravel." (Report of interview with G. Hogben, Hawke's Bay Herald, Aug 10)

OTANE (previously named Kaikora) & **PATANGATA:** "The effect of the earthquake in the Kaikora district was alarming … the ground cracked in hundreds of places, mud and sand being thrown up through the fissures. The brick flooring of a building for stabling prize sheep was thrown up and large stones, used for paving the ordinary stables displaced. In scores of places all over the river bed flats water rushed up through the cracks whilst the river bed rose, with the result that the drains were dammed back." (Hastings Standard, Aug 12 1904

"Early the following morning … on our way to Patangata in a buggy. When crossing the bed of the Waipawa River several jolts were felt and being curious as to the cause our surprise was great to find a number of cracks in the road running up and down stream and almost at right angles to the road. Examining more particularly it was noticed that the ground had been cracked and rifted in a variety of ways, and the whole area transformed into a miniature volcanic area minus the temperature. There were explosive craters truncated cones of sand with two or three central craters from which mud had been thrown [see Figure 4] there was a subsided area, one side of the fracture being lower than the other, blow-holes were numerous, and there was a line of elevation representing a miniature mountain range fractured in the middle and showing an anticline. (Hill, 1904a)

PORANGAHAU: "Along the shore between Porangahau and Blackhead, there have always been deposits of quicksand. Well, I am told by a person who often traverses that neighbourhood that some of the deposits have been moved and that it is now dangerous to walk along in some places. I have heard from two or three, that during the shake, a small creek near Porangahau closed and forced the water some considerable height into the air." (Hill, 1904a)

HERBERTVILLE: "All along the beach circular mud-holes were formed having the appearance of boiling pools. There were hundreds of these ranging in size from two to twenty feet in diameter; but after about three days nothing was to be seen of them." (Hill, 1904a)

AKITIO: "The shock was very severely felt on the coast and at Tautane, in the direction of Akitio, several small mud springs came into existence and I heard a few days ago that they were still active, oozing muddy water." (Hill, 1904a) Possibly the same place as the previous report.

WHAKATAKI: "At Whakataki… eight holes were blown in the ground, and mud ran out of them for several hours, while large cracks extending several chains were noticeable in many places." (Feilding Star, Aug. 13)

CASTLEPOINT: "The postmaster at Castlepoint further reports that within a radius of about half a mile the earth was cracked in several directions from an inch to 1 ½ inches wide. In several places from a bucket to two buckets of mud were thrown up." (Widely reported.)

GLADSTONE: "Following the earthquake shock and fall of earth off the cliffs at Gladstone, innumerable small holes appeared on the flat adjacent, spouting bluish mud and sand like miniature geysers. They ceased when the shake was over…. When the rumbling commenced … the river seemed to rise from its bed and fall back again, and the bridge swayed and reeled. McLaughlin's cliffs seemed to stagger, and then some thousands of tons of face fell with a roar into the Makaha creek, forcing the water over the flat, and strewing the land with eels and small trout. Mud and water shot into the air from a hundred holes in the earth around - like miniature volcanoes…. James Green, who was digging out an embedded rock nearby, was thrown violently, the ground opening under him a foot wide, spurting mud and water over him…. The flat presents an interesting spectacle, being punctured by numbers of small volcano-like craters, through which the mud and water spouted." (Manawatu Evening Standard, Aug. 12 1904)

"Mr Jensen of Waihakeke, says the Wairarapa Leader, was standing on the banks of the Ruamahanga when the earthquake came. He states that the most extraordinary spectacle in an extraordinary occurrence was the river. Its bed appeared to rise in undulating ridges and the water swirled away on the sides. Then suddenly as the earth rocked still more violently, the ridge disappeared and the waters, rushing together, there arose to a height of fully 100 feet, a geyser like volume of great stones, water and mud. These fell again with great splashes of foam." (Patea County Press, Aug, 19)

Waihakeke is slightly east of Greytown about 10 km from McLaughlin's cliffs. Possibly the same location as the previous Gladstone description, but surely this description is exaggerated!

Possible liquefaction

NEAR OPIKI: "It is reported that the earthquake the other day raised the Makerua swamp ... in places and that the drains which previously contained dead water are now carrying off their contents quite briskly."

Makerua swamp is an area a few kilometres south of Opiki. During the June 1942 earthquake sand and water were ejected at Opiki